Example 6.23: Liquefaction of Nitrogen

Nitrogen is liquefied in the process shown in Figure 6-16. Nitrogen gas is fed at 25 °C, 1 bar (stream 1). The gas is compressed to 180 bar in a compressor with an efficiency of 85%. The precooler uses ambient water as the cooling medium and cools the nitrogen to 30 °C. The precooler uses cold vapor from the separator as the cooling medium; this vapor leaves the precooler at 20 °C (stream). Perform the energy and entropy balances on the basis of 1 kg/s of liquid nitrogen produced.

Solution We will use the NIST WebBook to calculate the properties of nitrogen. The pressures of all streams are known: streams 1, 2, 6, 7, 8, and 9 are at 1 bar; streams 3, 4, and 5 are at 180 bar. Streams 6, 7, and 8 is the boiling temperature of nitrogen at 1 bar (−195.91 °C). We notice now that the state of streams 1, 7, 8, and 9 is fully defined and their properties may be collected from the Webbook (see summary table below). In addition to the usual properties (P, T, H, S, and phase) we must also include in the table of streams the flow rates, since these are not the same among all streams. We set the basis to be 1 kg of liquid nitrogen in stream 7, and the unknown flow rate of vapor stream 8 to be x. By straightforward material balance, the flow rate of stream 1 is 1 kg/s, the flow rate of streams 8 and 9 are x, and all other flow rates are $x+1$. The known properties of the streams are summarized below:

	1	2	3	4	5	6	7	8	9
$\dot{m}$	1	$x+1$	$x+1$	$x+1$	$x+1$	$x+1$	1	x	x
P	1	1	180	180	180	1	1	1	1
T	25			30		195.91	195.91	195.91	25
H	309.27			285.15			−122.25	77.073	309.27
S	6.8392			5.2159			2.8312	5.411	6.8392

Here, $\dot{m}$ is the flow rate on the basis of 1 kg of liquid nitrogen, P is in bar, T is in °C, H is kJ/kg, and S is kJ/kg K.

First we perform an energy balance around a subsystem defined by the cooler, throttling valve, and separator. This part of the process exchanges no heat of work with the surroundings and involves three streams, stream 4 going in and streams 7 and 9 coming out.

Cooler/throttling/separator. The subsystem defined by the precooler, the throttling valve, and the separator exchanges no heat or work with the surroundings and it involves 3 streams (4, 7, and 9) whose properties are known. The unknown flow rate x may be determined by application of the energy balance:

$$xH_{\underline{7}}{}_{9} + 1 \times H_{\underline{9}}{}_{7} = (1+x)H_4 \quad \Rightarrow \quad x = \frac{H_7 - H_4}{H_4 - H_9} = 16.89 \text{ kg/s}.$$

With this, all mass flow rates are now known. Since all vapor in stream 6 exits as stream 8 and all liquid exits as stream 7, the liquid and vapor fractions in stream 6 are

$$x_L = \frac{m_7}{m_7 + m_8} = 0.0559, \quad x_L = 1 - x_V = 0.9441.$$