10.40 Thermodynamics **Fall 2003**
Exam 1

Problem 2

2. (30 points) *Technology Review* (December 1975) describes a new invention for producing power – the Nitinol Engine. "Nitinol is a unique nickel-titanium alloy whose mechanical and electrical properties change drastically during a crystalline phase change [occurring at] modest temperatures [about 40^{o}C]. The result is a memory for shape: if deformed while cool, nitinol will return to its undeformed shape when warmed. Alternately heating and cooling it causes motion – a conversion of heat to mechanical energy." The article also contained the illustration shown below and a quote by A.D. Johnson who claims that 30 W of shaft output were generated with a hot water stream flowing at 10 grams/s at 50^{o}C.

MITY Industries needs your help to decide whether it should apply for a patent based on Johnson's invention. Develop an appropriate analysis to evaluate whether the claim is thermodynamically viable. If your analysis shows that the Nitinol engine is thermodynamically viable, is the claimed output possible from a practical point of view? You can assume favorable conditions where a very large flow of cold water is available at 20^{o}C.

Image removed due to copyright considerations. Please see "*Technology Review* 78, no.2 (December 1975): 19."

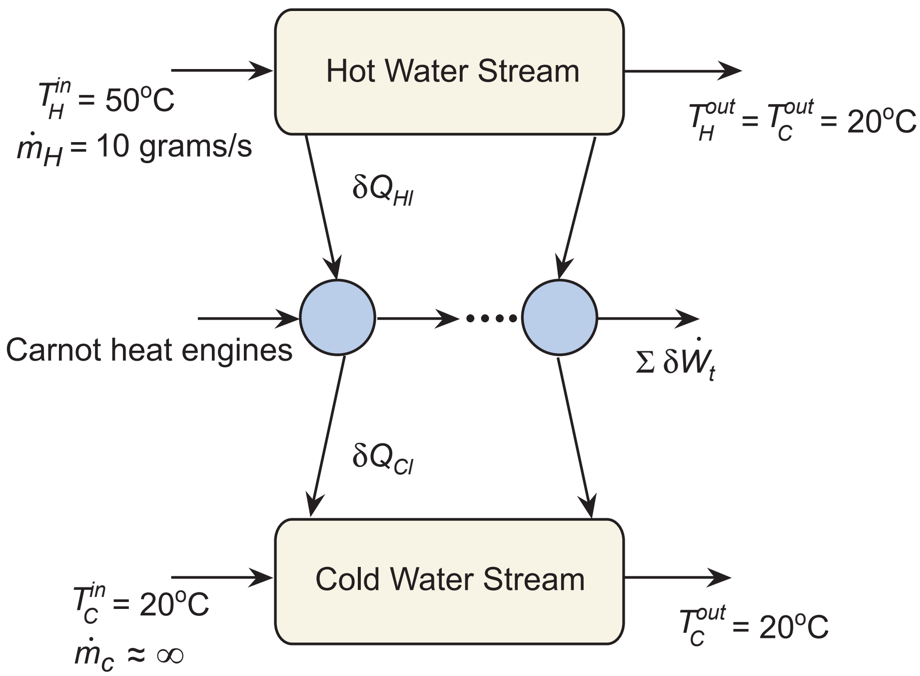
Solution

In order to determine if the process is thermodynamically viable, it is necessary to calculate the maximum power under reversible conditions.

This problem can be solved with or without availability.

<u>Method 1: Without Availability</u>

This problem can be solved using the same method as example problem 4.5. The Nitinol Engine can be modeled as a series of Carnot Engines. Since we have a very large flow of cold water available to the process and we want to abstract the maximum work from the hot stream, we can assume that the cold stream temperature is constant throughout the process and that the hot stream exits the process at the same temperature as the cold stream.



Adapted from Tester, J. W. and Modell, Michael. *Thermodynamics and Its Applications*. Upper Saddle River, NJ: Prentice Hall PTR, 1997, p. 91, Fig. 4.7.

Image by MIT OCW.

Assume that C_p is that of liquid water, that it is constant for the entire process and that it is equal to 4186 J/kg K.

Applying the first law to the heat engines and using the Carnot efficiency as was done in example 4.5,

$$\dot{W}_{\max} = \dot{m}_H C_p \int_{T_H^{in}}^{T_H^{out}} \frac{T_H - T_C}{T_H} dT_H \tag{1}$$

$$\dot{W}_{\max} = \dot{m}_H C_p \left[T_H^{out} - T_H^{in} - T_C \ln\left(\frac{T_H^{out}}{T_H^{in}} \right) \right]$$

$$\dot{W}_{\max} = \left(0.010 kg/s\right)\left(4186 J/kgK\right)\left[293 - 323 - 293 \ln\left(\frac{293}{323} \right) \right]$$

$$\dot{W}_{\max} = -60\, W$$

The maximum work producing potential of the Nitinol Engine is 60 W, which is greater than the claimed 30 W. Thus, Johnson's claim is thermodynamically viable.

<u>Method 2: With Availability</u>

This problem can be solved in a manner similar to Example 14.1. We calculate the maximum available energy of the hot water stream when it can reject heat to the cold water stream.

$$\dot{W}_{\max} = \dot{m}_H \Delta B = \dot{m}\left(\Delta H - T_0 \Delta S\right)$$
$$T_0 = T_C = 20°C \qquad (2)$$

From first law analysis and equation 4-29, text,

$$\Delta H = \int_{T_H^{in}}^{T_C} C_p dT$$
$$\Delta S = \int_{T_H^{in}}^{T_C} \frac{C_p}{T} dT \qquad (3)$$

Integrating equation (3) and plugging the result into equation (2) yields

$$\dot{W}_{\max} = \dot{m}_H C_p \left[T_H^{out} - T_H^{in} - T_C \ln\left(\frac{T_H^{out}}{T_H^{in}} \right) \right]$$

which is the same as equation (1) that we derived without using availability. The solution then follows the Method 1 solution.

Feasibility Evaluation

To answer the question of whether or not the claimed output is possible from a practical point of view, we first examine the claimed utilization efficiency. Since the Nitinol Engine is a type of heat engine, we can evaluate the utilization efficiency using equation 14-25, text.

$$\eta_u \equiv \frac{\dot{W}_{net}}{\dot{m}\Delta B}$$
$$\eta_u = \frac{30\,W}{60\,W} = 50\%$$

Since the utilization efficiency for low temperature plants is usually in the range of 50% to 65% (page 595, text), a 50% percent utilization efficiency seems feasible.

To further refine our answer we check the cycle efficiency using figure 14.16. We can calculate the cycle efficiency from the utilization efficiency.

$$\eta_{cycle} = \eta_u \eta_{carnot} = \eta_u \left(\frac{T_H - T_C}{T_H} \right) = 0.50 \left(\frac{323 - 293}{323} \right) = 5\%$$

Examining figure 14.16 at our T_H of 50°C, we find that heat cycles that commonly operate at that temperature have cycle efficiencies from 1% to 6%. Thus, our cycle efficiency of 5% falls within the range of known processes and could be practically feasible.