THERMODYNAMICS

The Principles of Thermodynamics and Their Application to Engineering Processes

BY

LESTER C. LICHTY

Associate Professor of Mechanical Engineering, School of Engineering, Yale University

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The Regenerative Cycle.*—This cycle bleeds or abstracts a portion of the medium flowing through a turbine (Fig. 52), in which it has been partially expanded and has done some Work,

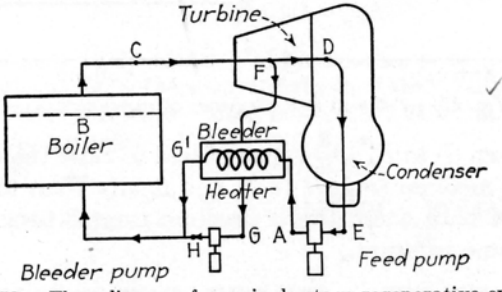

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FIG. 52.—Flow diagram for a single-stage regenerative cycle.

and makes use of the medium abstracted for heating feed water. This reduces the Work done per unit weight of medium but also *reduces to a greater degree* the amount of Heat which must be supplied to the cycle. A turbine with a single stage of bleeding would expand the medium from C to F (Fig. 53) and then bleed sufficient medium (M lb.) to raise the feed water from A to the temperature at G' corresponding to the saturated condition of the medium at bleeding pressure.

* Medium is often bled or extracted from turbines and used for purposes other than heating the feed water. In such cases the Work is obtained in the same manner as in the regenerative cycle but the Heat supplied would be greater.

Since, the transfer of Heat from the bled medium is equal to that transferred to the feed water, and since this occurs at constant pressure in both cases,

$$M(H_F - H_G) = (1 - M)(H_{G'} - H_A) \tag{1}$$

The M lb. of bled medium are condensed in this process and then pumped into the feed line as indicated by GH. The boiler must supply Heat to raise the temperature of $(1 - M)$ lb. of

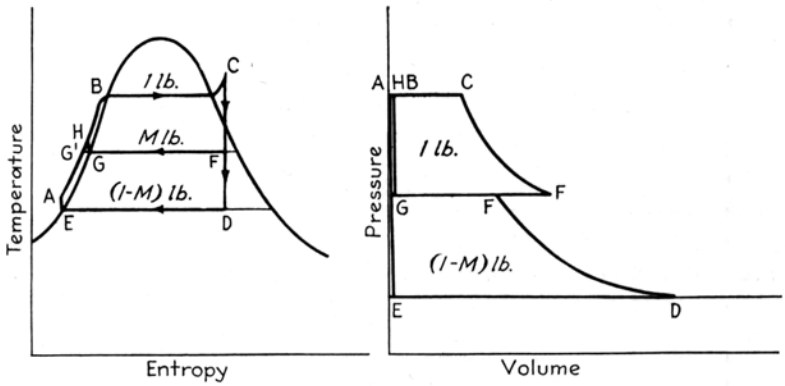

FIG. 53.—T-S and P-V diagrams of regenerative cycle.

medium from G' to B, also enough Heat to raise the temperature of M lb. of medium from H to B, and finally Heat to change the condition of both quantities of medium from B to any condition C at the same pressure.

Thus, $$Q_{in} = (H_C - H_H) + (H_H - H_{G'})(1 - M) \tag{2}*$$
and, $$Q_{out} = (H_D - H_E)(1 - M) \tag{3}$$

Then for the cycle,

$$W_{out} - W_{in} = Q_{in} - Q_{out} = (H_C - H_H) + (H_H - H_{G'})(1 - M) - (H_D - H_E)(1 - M) \tag{4}$$

This cycle can be analyzed as two separate cycles, one with M lb. of medium following cycle $HBCFG$, and the other with $(1 - M)$ lb. of medium following cycle $ABCDE$. Applying the steady-flow analysis to the engine and pump sections of each cycle results in,

* The difference between H_H and $H_{G'}$ or H_G is usually negligible.

$$(W_{out} - W_{in})_{cycle} = [(H_C - H_F) - (H_H - H_G)]M + [(H_C - H_D) - (H_A - H_E)](1 - M) \quad (5)$$

in which each bracketed term is the difference between engine and pump Work for that cycle. It follows from Eq. (5) that the Work of the turbine is

$$W_{turbine} = (H_C - H_F)M + (H_C - H_D)(1 - M) \quad (6)$$

The use of an infinite number of stages with bleeding at pressures ranging from C to D results in feed water arriving at the boiler at the condition at B (Fig. 53). If C was in the saturated region all of the Heat added to the cycle would be added at the highest temperature. Since the only Heat that is rejected from the cycle is rejected at the lowest temperature, it follows that the efficiency of this cycle with an infinite number of bleeding stages would equal that of the Carnot cycle with the same temperature limits. Thus, the efficiency of the Rankine cycle is improved with the incorporation of bleeding stages for regenerative purposes.

Example.—Determine the efficiency of the Rankine cycle in the example on page 120 with one stage of bleeding at 50 lb. in.$^{-2}$ abs. Initial conditions are 500 lb. in.$^{-2}$ abs. and 700°F. Back pressure is 0.95 lb.. in.$^{-2}$ abs.

From Chart A, Appendix, $H_F = 1138.3$ B.t.u.
From Table V, $H_G = 249.98$ B.t.u.

$$H_{G'} = H_G + (P_{G'} - P_G)V_G = 249.98 + \frac{144(500 - 50)0.01724}{778} = 251.4 \text{ B.t.u.}$$

H_A from the previous example = 69.4 B.t.u.
Substituting in Eq. (1),

$$M(1138.3 - 250.0) = (1 - M)(251.4 - 69.4)$$

or $$M = 0.170 \text{ lb.}$$

also,
$$H_C - H_F = 1356.6 - 1138.3 = 218.3 \text{ B.t.u.}$$
$$H_H - H_G = H_{G'} - H_G = 1.4 \text{ B.t.u. approx.}$$
$$H_C - H_D = 1356.6 - 897.2 = 459.4 \text{ B.t.u.}$$
$$H_A - H_E = 1.5 \text{ B.t.u. from the previous example.}$$

Substituting in Eq. (5),

$$(W_{out} - W_{in})_{cycle} = (218.3 - 1.4)0.170 + (459.4 - 1.5)0.830 = 416.9 \text{ B.t.u.}$$
$$Q_{in} = (H_C - H_H) = 1356.6 - 251.4 = 1105.2 \text{ B.t.u.}$$
$$\text{Cycle efficiency} = \frac{W_{out} - W_{in}}{Q_{in}} = \frac{416.9}{1105.2} = 0.378$$

Although the net Work out is less, the Heat added is sufficiently less to increase the efficiency of the cycle from 0.356 to 0.378 by the introduction of one stage of bleeding at 50 lb. pressure.

The most desirable pressure at which to bleed medium from a bleeding turbine can be determined by choosing a number of pressures and solving the cycle for each pressure. Obviously, as the bleeding pressure approaches the initial pressure or back pressure the efficiency of the bleeding cycle approaches that of the Rankine cycle.

The Reheating Cycle.—The medium in this cycle is removed from the turbine after partial expansion, is reheated in special

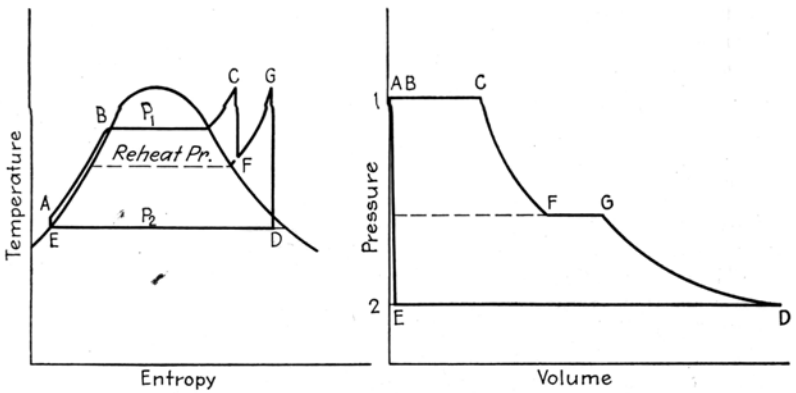

FIG. 54.—T-S and P-V diagrams of a single-stage reheating cycle.

resuperheating surface in the boiler, and then expanded to the back pressure in the turbine. The condition of the medium at the beginning of reheating (F, Fig. 54) may be in either the mixture or superheated region, and the temperature of the reheated medium at G may not be equal to the temperature of the medium at C. Both expansions, CF and GD, are assumed to occur adiabatically without friction in the ideal case.

Since, both the heating and reheating of the medium occur at constant pressure the Heat added can be evaluated in terms of Enthalpy change. Thus,

$$Q_{\text{in}} = (H_C - H_A) + (H_G - H_F) \tag{1}$$

and,

$$Q_{\text{out}} = (H_D - H_E) \tag{2}$$

Then, for the cycle,

$$W_{out} - W_{in} = Q_{in} - Q_{out} = (H_C - H_A) + (H_G - H_F) - (H_D - H_E) \quad (3)$$

$$= [(H_C - H_F) + (H_G - H_D)] - [H_A - H_E] \quad (4)$$

in which the turbine Work is given in the first and the pump Work in the second bracket. This relation could be arrived at directly from a steady-flow analysis of the turbine and of the feed pump.

Example.—A reheating turbine is supplied with superheated water vapor at 500 lb. in.$^{-2}$ abs. pr. and 700°F. The steam is expanded adiabatically without friction to a pressure of 100 lb. in.$^{-2}$ abs. It is then reheated to 700°F. and expanded to 0.95 lb. in.$^{-2}$ abs. pr. Determine the efficiency of the reheating cycle and compare with the Rankine cycle operating between the same initial and back-pressure conditions.

From Table VI or Chart A, Appendix,

H_C at 500 lb. in.$^{-2}$ and 700°F. = 1356.6 B.t.u.

H_F = 1192.8 B.t.u., H_G = 1378.2 B.t.u. and H_D = 1004.2 B.t.u.

From the example on page 120, for which the same data are given,

H_A = 69.4 and H_E = 67.9 B.t.u.

Substituting in Eq. (4),

$$W_{out} - W_{in} = [(1356.6 - 1192.8) + (1378.2 - 1004.2)] - [69.4 - 67.9]$$
$$= 537.8 - 1.5 = 536.3 \text{ B.t.u.}$$

Also, $Q_{in} = (H_C - H_A) + (H_G - H_F)$ Eq. (1)

$$= (1356.6 - 69.4) + (1378.2 - 1192.8) = 1472.6 \text{ B.t.u.}$$

$$\text{Reheating cycle efficiency} = \frac{W_{out} - W_{in}}{Q_{in}} = \frac{536.3}{1472.6} = 0.364$$

which is greater than the Rankine cycle efficiency of 0.356 for the same initial and back-pressure conditions (see example on page 120).