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THERMODYNAMIC ANALYSIS OF A GEOPRESSURED GEOTHERMAL HYBRID WELLHEAD POWER SYSTEM

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h .... enthalpy of steam, Btu/lbm

Δh .... change of enthalpy of steam, Btu/lbm

m .... mass flow rate of steam, lbm/hr

m_{br} .... mass flow rate of brine, lbm/hr

P .... pressure, psi

Q .... heat transfer rate, Btu/hr

q.... heat transfer rate per unit mass flow rate, Btu/lbm

s .... entropy of steam, Btu/lbm-°R

T .... temperature, °F

W .... turbine power output, Btu/hr or kw

W .... turbine work per unit mass flow rate, Btu/lbm

g .... quality of steam

Chapter 1

Introduction

This research project is designed to evaluate the performance and operating characteristics of hybrid power cycles applied to geopressured and geothermal resources. The power systems evaluated are from the EPRI geopressured wellhead project and data used for the analysis are from the Pleasant Bayou well site.

Preliminary design considerations indicate that hybrid power cycles utilizing heat, methane gas and hydraulic energy from the reservoir should be the preferred method of developing power from geopressured resources. Also, EPRI anticipates that combustion-hydrothermal hybrid cycles, without the pressure recovery component, can be applied in the development of hydrothermal reservoirs for power generation. The performance of the pressure reducing component is not included in this thermodynamic analysis.

Three types of hybrid power systems are analyzed thermodynamically in this project. They are (A) the single flash system, (B) the double flash system, and (C) the binary system. The studies of the first two systems are more extensive than the third one, although the binary system is the one chosen for testing at the Pleasant Bayou well site.

Chapter 2

Objectives of the Project

The objectives of the project are the following:

1. Perform thermodynamic evaluations of a preliminary design utilizing a gas engine-topped single-flash installation.
2. Perform thermodynamic evaluations of a preliminary design utilizing a gas engine-topped double-flash installation.
3. Perform thermodynamic evaluations of a modified binary system from the preliminary design of a compound hybrid geothermal-fossil power plant.

The thermodynamic evaluations are bases on models presented in "Project Description for EPRI Feasibility Assessment of a Geo-pressured Geothermal Wellhead Power System" prepared by C. K. Geoenergy Corporation for the Electric Power Research Institute. Minor changes in the single-flash and double flash systems are made in order to stress the key parameters in the thermodynamic cycle analysis. It has been determined that a modification of the proposed binary cycle might add additional power output. The EPRI geopressured geothermal wellhead power systems are briefly discussed in the next section.

Chapter 3

The EPRI Geopressured Geothermal Wellhead Power System

The principal components and subsystems of the hybrid power plant are as follows:

1. The Pleasant Bayou No. 2 production well and reservoir.
2. The Pleasant Bayou No. 1 injection well and reservoir.
3. A pressure reduction turbine/generator (PRT)
4. Gas separator facilities.
5. A membrane gas enrichment plant
6. A gas engine (GE) or gas turbine (GT) generating unit.
7. A heat recovery system for combustion heat input to the bottoming cycle.
8. A heat rejection system
9. Option A: A flashed steam power system with either a single stage flash (Fig. 1) or a double stage flash (Fig. 2) bottoming cycle.
10. Option B: A binary cycle power system (Fig. 3)

In our report, the thermodynamic analyses are based on the above mentioned single stage flash or double stage flash system. A modified binary cycle is used to replace the above mentioned binary cycle. These analysis are discussed in the following sections.

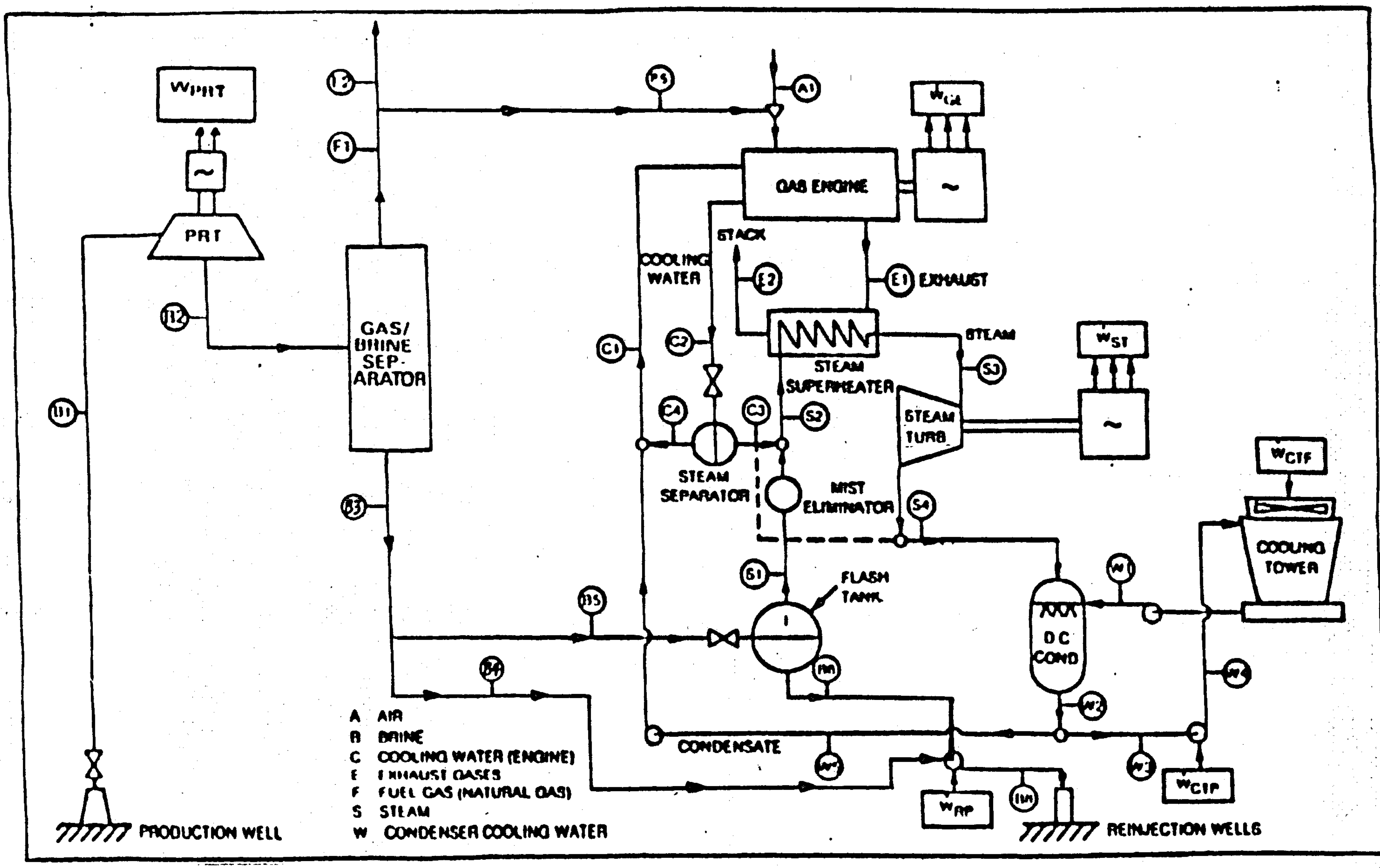

Fig. 1 Flow Diagram of an EPRI Gas Engine-Topped Single Flash System

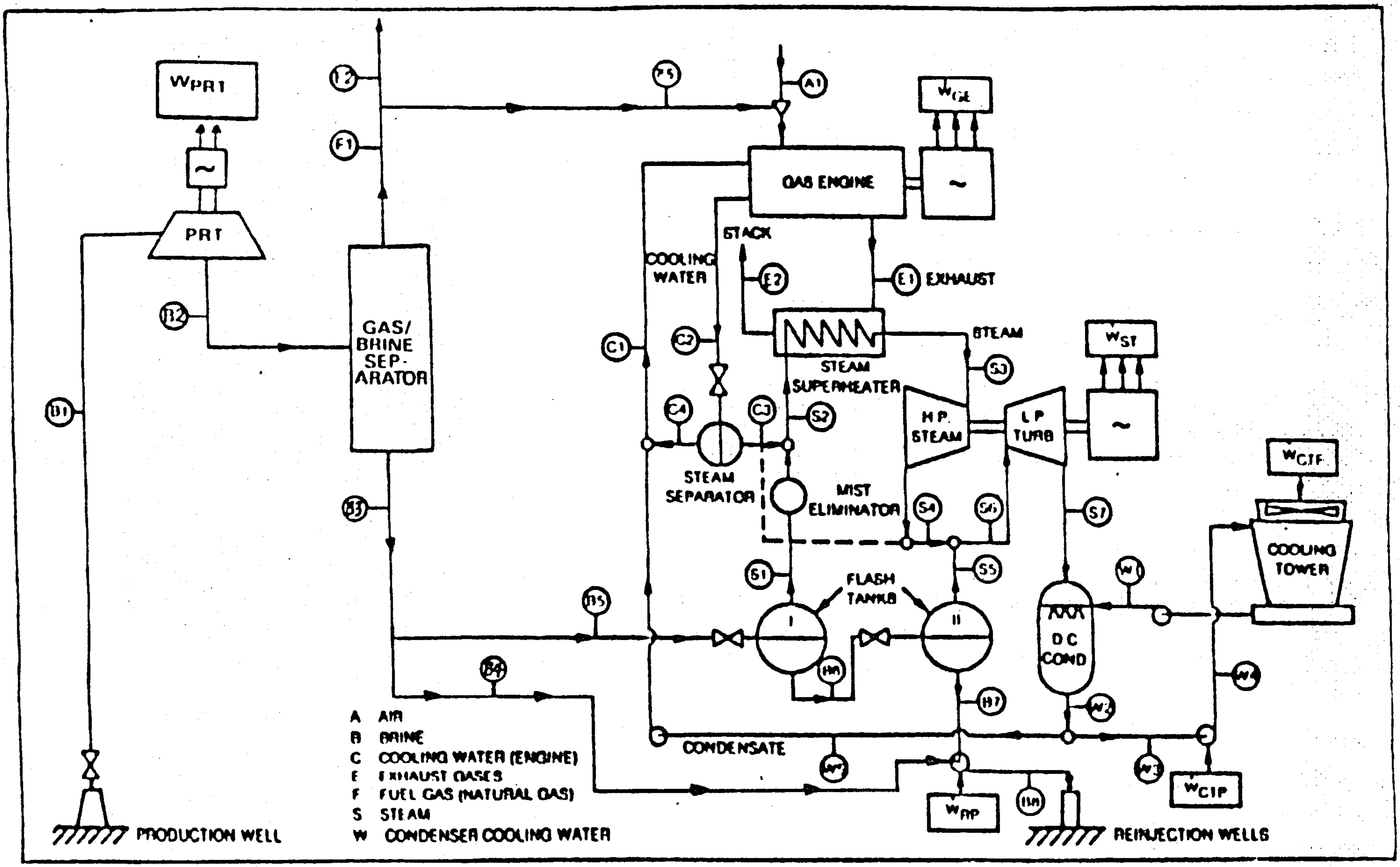

Fig. 2 From Diagram of an EPRI Gas Engine - Topped Double Flash System

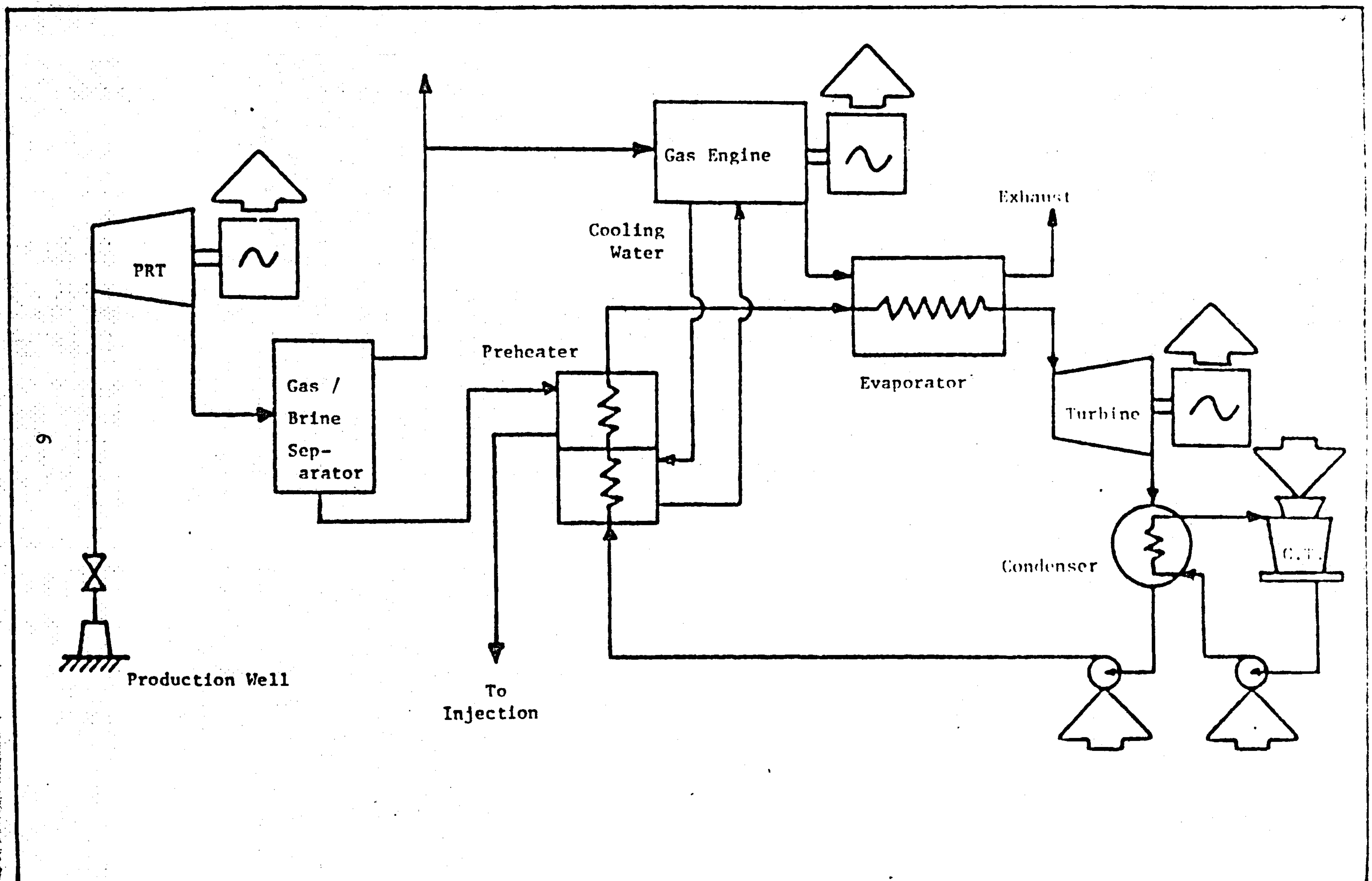

Fig. 3 From Diagram of An EPRI Gas Engine - Topped Binary System

Chapter 4

Gas Engine - Topped Single-Flash System

4.1 Single Flash System

The main purpose of our thermodynamic analysis of the single flash system is to determine the optimal flashing condition in order to achieve maximum power output, and to determine the effect of superheating from exhaust heat to this optimal flashing condition. To serve this purpose, the flow diagram of a single flash system for our analysis is shown in Fig. 4, which is derived from the EPRI single-flash system (Fig. 3) without the pressure reducing turbine, brine-gas separation units, etc.. The system shown in Fig. 4 is a typical Rankine cycle, in which the steam is generated by flashing brine through an expansion valve while superheated steam is obtained by transferring exhaust heat to a heat exchanger. Based on the second law of thermodynamics, the power output of this cycle can be increased by decreasing the condenser pressure (thus decreasing the temperature at which the heat is rejected), or increasing the degree of superheating (especially since the heat source is the exhaust heat of the gas engine, which is going to be rejected to the atmosphere if it has not been used). The power output can also be increased by increasing the temperature of the steam in the flash tank and by increasing the mass flow rate of steam in the cycle. However, for a constant flow rate of brine entering the system, the mass flow rate of steam obtained through flashing and the temperature of steam in the flash tank are dependent. Increasing the mass flow rate will decrease the temperature and vise versa.

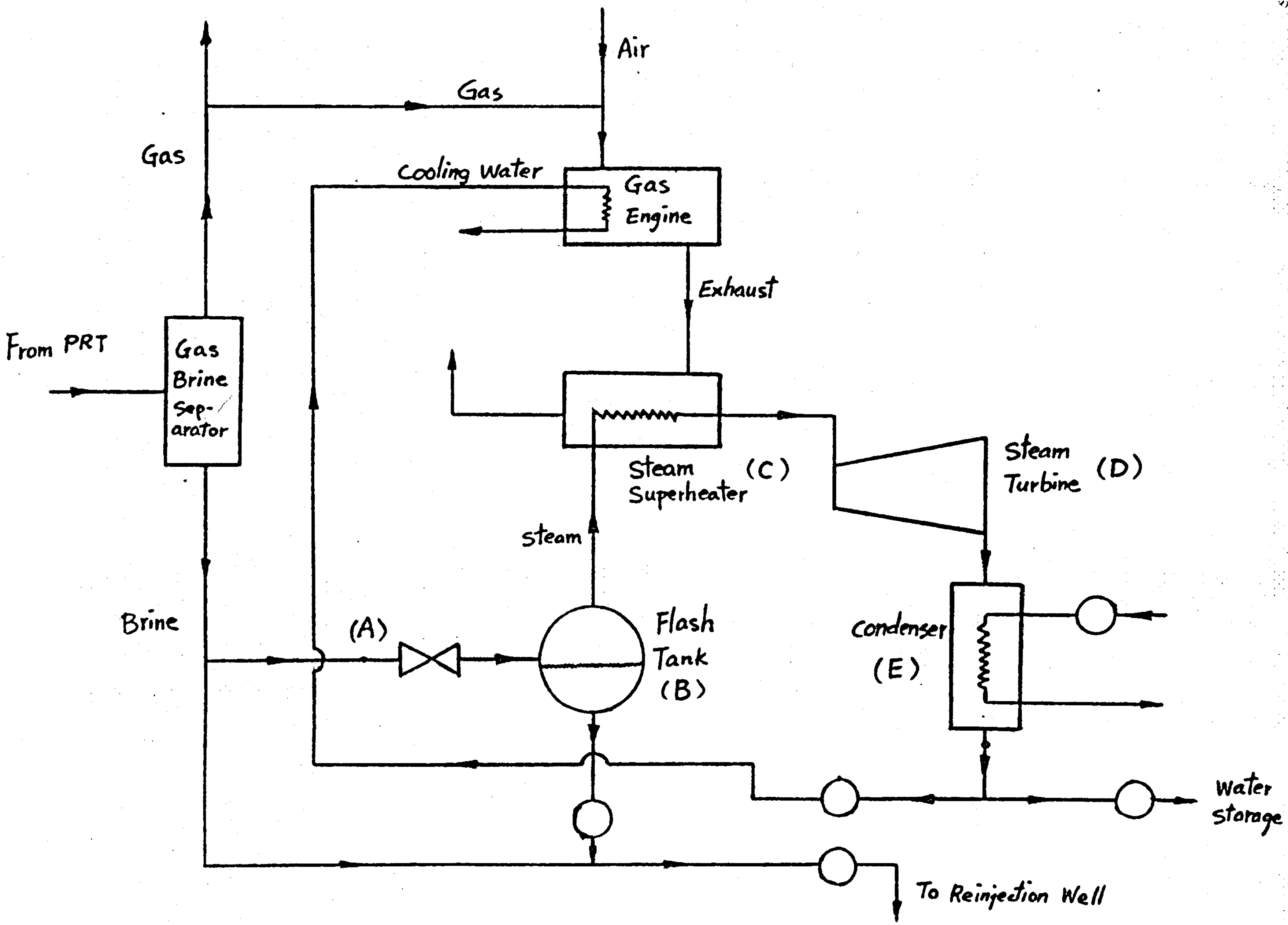

Fig. 4 From Diagram of an EPRI Gas Engine - Topped Single Flash System

Therefore, an optimal flashing condition should exist. In the next section, we will determine this flashing condition.

4.2 Optimal Flashing condition

With reference to Figure 4, assume the mass flow rate of brine M_{br} to be constant and enters the expansion valve at a fixed pressure and temperature of Pa and Ta respectively. Assume the amount of superheating represented $m(\Delta h_c)$ is also constant, in which m is mass flow rate of steam and Δh_c is the change in enthalpy of steam through the steam superheater. Let the pressure at steam condenser be constant at Pe. Then, the power output of the system should depend on the flashing condition only and can be computed by the equation

$$We = m \Delta h_D \quad \cdots\cdots (1)$$

in Δh_D is the change of enthalpy of steam through the turbine. Mass flow rate m and Δh_D are determined in the rest of the section. From the geothermal reservoir, the brine temperature Ta usually is not high. Since the condenser pressure Pe is not much lower than atomospheric pressure, so the corresponding saturation temperature of steam Te is not much lower than Ta. In the flash tank, the steam temperature Tb is always between Ta and Te, Therefore the variation of this temperature is within a relative small range. With this limited temperature variation in mind, a T-S diagram of steam in saturation condition is shown in Fig. 5. Note that the saturated liquid line, saturated vapor line, and constant enthalpy line are all approximated by straight lines.

From thermodynamics, we have

$$m = xm_b \text{ -----} \quad (2)$$

$$x = \frac{S-S_f}{S_{fg}}$$

In which x represents the quality of steam in flash tank. Since S_{fg} is much larger than $(S-S_f)$ and does not varied much as shown in Fig. 5. Therefore,

$$x = \frac{S-S_f}{S_{fg}} = (\text{const } 1)\ (S-S_f) \text{ ----} \quad (3)$$

Also from Fig. 5, we are able to approximate $(S-S_f)$ by

$$\frac{S-S_f}{Se} = \frac{Ta-Tb}{Ta-Te}$$

or

$$S-S_f = (Ta-Tb)\left(\frac{\Delta Se}{Ta-Te}\right) = (\text{const } 2)\ (Ta-Tb) \text{ ----} \quad (4)$$

Finally, we have

$$m = (m_{br})(\text{const } 1)\ (\text{const } 2)\ (Ta-Tb) \text{ ---} \quad (5)$$

Now we shall evaluate Δh_D at the steam turbine. On the h-s diagram shown in Fig. 6, along the saturated vapor line, the temperature scale is more or less evenly divided for the temperature range involved. For a given amount of superheating, Δh_c is inversely proportional to m, or to (Ta-Tb). This means an increase of (Ta-Tb) represents a decrease of Δh_c. Therefore, refer to Fig. 6, point c in the figure is located approximately on the same vertical line when Tb is varied within a small temperature range which included the optimal condition. Let Δh represent the length of that vertical line which is a constant for a given

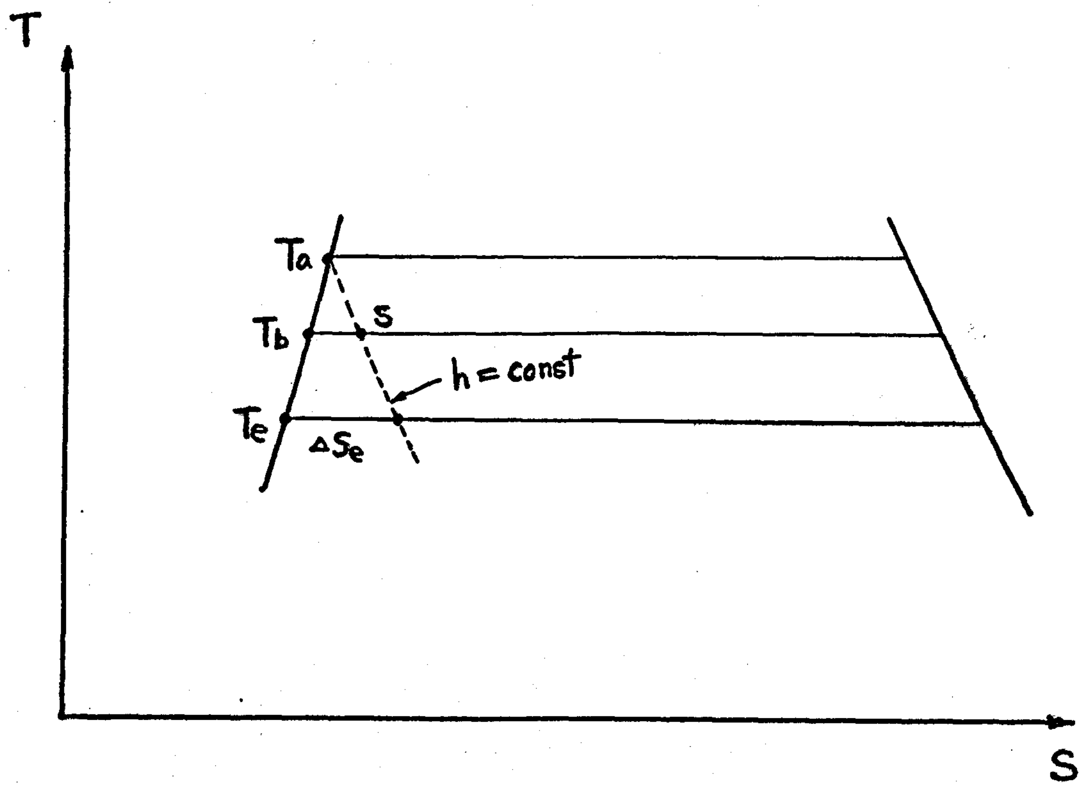

Fig. 5 T - S Diabram of Saturated Steam at Low Temperature

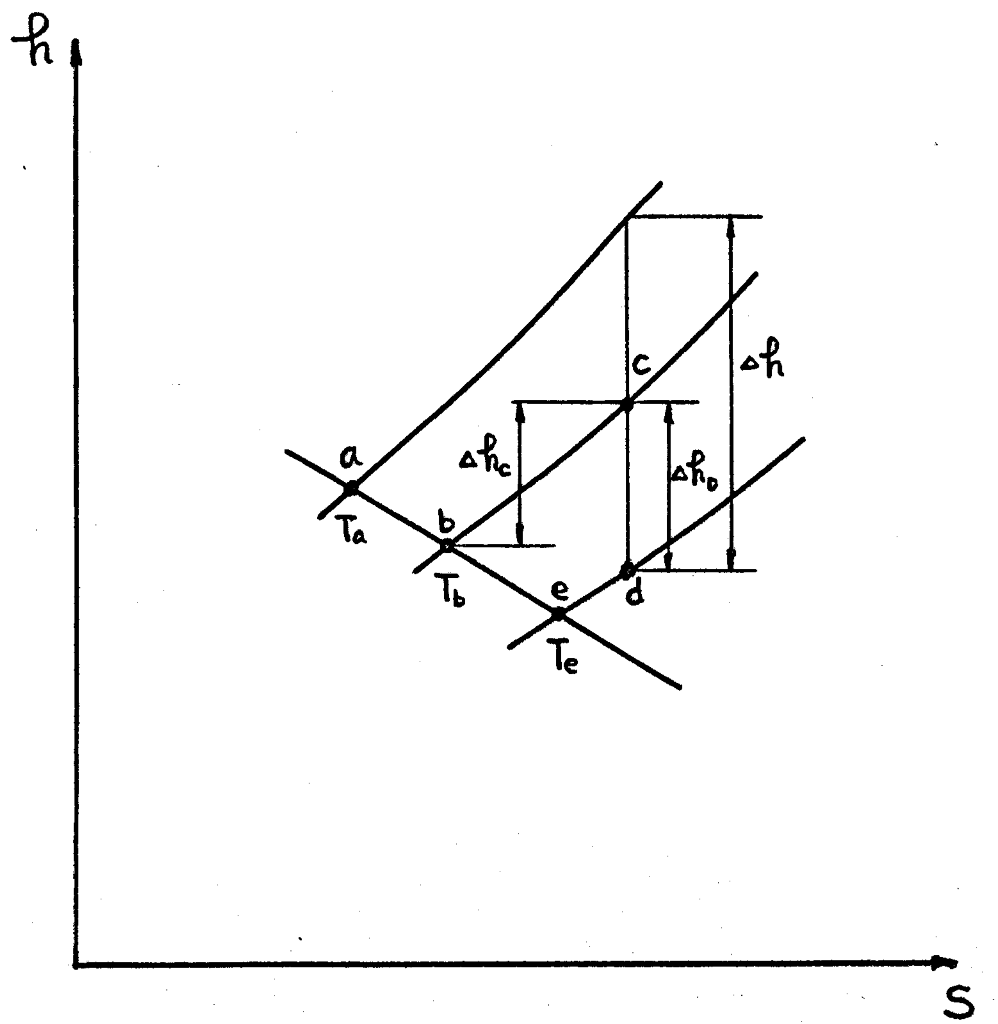

Fig. 6 H - S Diagram of Saturated Steam at Low Pressure

amount of superheating. From Figure 6

$$\Delta h_D = \left(\frac{Tb-Te}{Ta-Te}\right) h$$

$$\Delta h_D = (\text{const } 3)\ (Tb-Te) \quad \text{----} \quad (6)$$

Substitute Eq (6) and (5) into (1), we have

$$W_e = m\Delta h_D$$

$$W_e = (m_{br})\left(\frac{1}{S_{fg}}\right)\left(\frac{\Delta Se}{Ta-Te}\right)\left(\frac{\Delta h}{Ta-Te}\right)(Ta-Tb)(Tb-Tc) \qquad (7)$$

From $\frac{\partial W_e}{\partial Tb} = 0$, and solving for Tb (7)

$$T_b = \frac{Ta + Te}{2} \qquad (8)$$

For the maximum power output of the cycle, the temperature at the flash tank is the arithmetic mean of the brine temperature as it enters the expansion valve and the saturation temperature at the condenser. This optimal condition is independent of the amount of superheating involved according to Equ. (8). Of course, the power output W_e of the cycle is dependent on superheating as indicated by Equ. (7), in which Δh is varied by the amount of superheating involved.

The validity of the optimal condition expressed by Equ. (8) is verified in the next section. Where the steam tables are used for more precise computations.

4.3 Thermodynamic Analysis of a Gas Topped Single Flash System

For purposes of comparision, data from the EPRI system are used to numerically evaluate the performance of a gas topped single flash system under various operation conditions. The flow diagram of the system with labels for easy reference is in Fig. 7 (which is from Fig. 4). The data suitable for computations are summarized in Table 1.

The main purpose of the analysis is to obtain the net power output of the system which is the difference between the power output at the steam turbine and the power input requirements at the various pumps. A sample computation including pump work is shown in Table 2. This computation shows that the power input at various pumps is very small when compared with the steam turbine power output. Therefore, this contribution will be neglected during the remainder of the analysis.

With reference to Figure 7 where the brine enters the expansion valve at section (9) with a flow rate of 292000 lbm/hr, the pressure is 200 psia and the temperature is 280°F. Assuming brine acts much like water thermodynamically, the corresponding saturation pressure is 49.2 psia. This means the pressure at flash tank has to be less than 49.2 psia in order to generate steam. By assuming a pressure at flash tank (for example, the first chosen value is 45 psia), with a given heat transfer rate $_5Q_6$ from exhaust heat of gas engine at steam superheater, the power output $_{17}W_{18}$ at steam turbine can be easily computed. Then, change only the pressure at flash tank (for example, decrease the pressure by 5 psia), and repeat the same

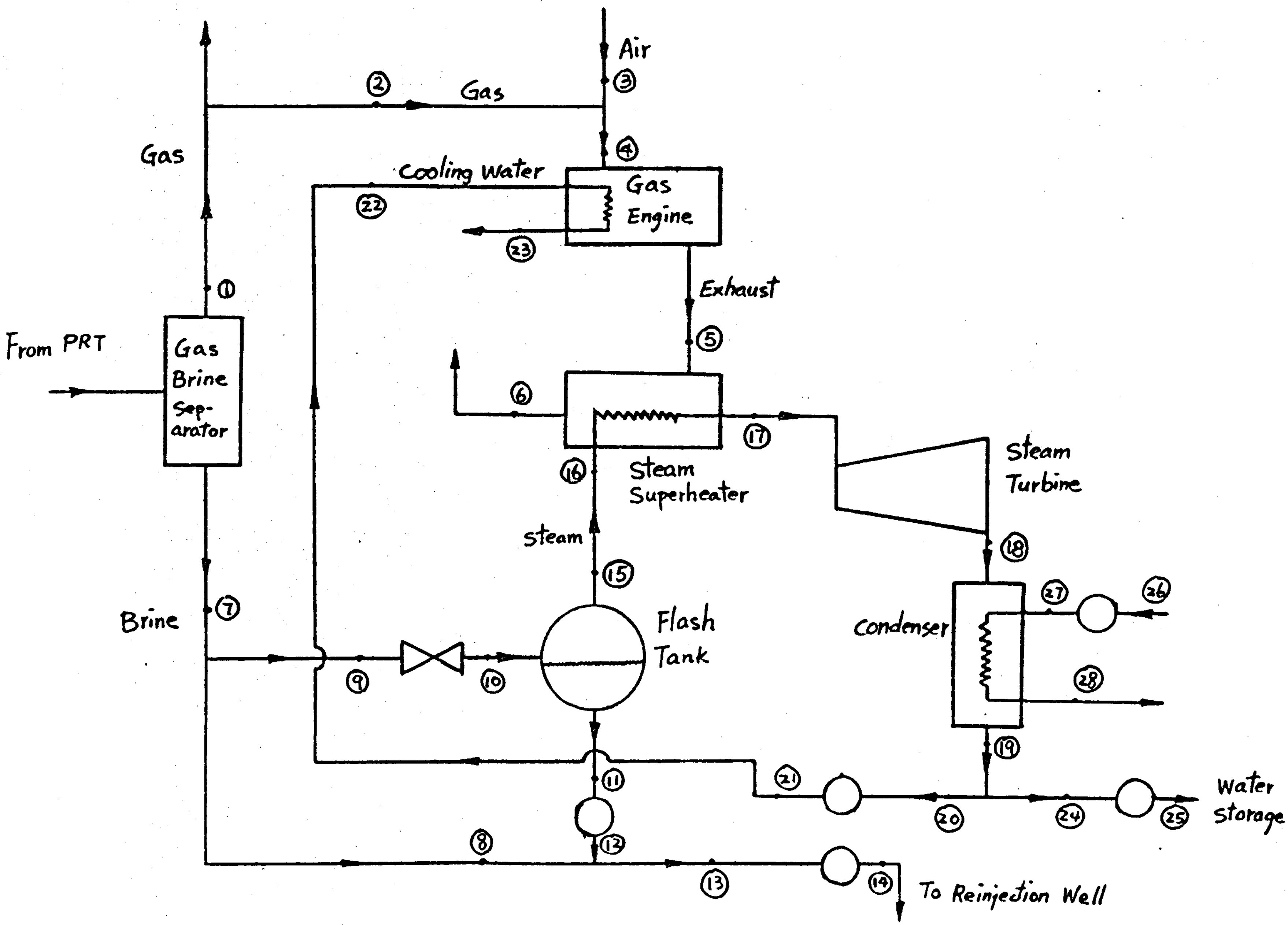

Fig. 7 Flow Diagram of A Gas Engine Topped Single Flash System with Section Numbers

mass flow rate of brine	20,000 bbl/day
	= 292000 lbm/hr
temperature of brine before expansion	280 °F
pressure of brine before expansion	200 psia
pressure at the condenser	8 psia
Exhaust gas of gas engine leaving steam superheater	915 °F

Table 1 Some of the Data used for Single and Double Flash System Computations

For $_5\dot{Q}_6 = 107{,}930$ Btu/hr and $P_{10} = 20$ psia

$x_{10} = 0.05510$, $T_{10} = 227.96\,°F$

$T_{16} = 227.96\,°F$, $\dot{m}_{16} = 16089$ lbm/hr

$h_{16} = 1156.3$ Btu/lbm

$h_{17} = 1163.0\ \frac{Btu}{lbm}$, $S_{17} = 1.7415\ \frac{Btu}{lbm\text{-}°R}$

$T_{17} = 241.4\,°F$

$x_{18} = 0.9583$, $h_{18} = 1098.1\ \frac{Btu}{lbm}$

$_{17}\dot{W}_{18} = 1{,}044{,}180$ Btu/hr

$h_{19} = 150.79$ Btu/lbm

$\dot{m}_{30} = 304{,}825$ lbm/hr

$\dot{W}_{P\,cond.} = 9150$ Btu/hr

$\dot{W}_{net} = {_{17}\dot{W}_{18}} - \dot{W}_{P\,cond.} = 1{,}035{,}030$ Btu/hr

Table 2 Net Power Output of a Single Flash System that Excludes the Condenser Pump Work computations for power output $_{17}W_{18}$ at the steam turbine. Continuing the above procedures, we are able to obtain the relation between power outputs at the steam turbine and the conditions at flash tank. The optimal flashing condition then can be determined. This result can be compared with the theoretical estimation in the last section. The above analysis should be repeated for different heat transfer rates $_5Q_6$ from the exhaust heat of a gas engine.

All computations involve the use of a number of simple thermodynamic equations and steam tables. Assuming ideal thermodynamic processes, without heat loss and pressure drop in piping, the following equations are used.

$$X_{10} = \frac{249.06 - h_{f10}}{h_{fg10}}$$

$$m_{16} = X_{10}\,(Mq)$$

$$T_{10} = T_{16} \qquad (9)$$

$$h_{17} = \frac{_5Q_6}{m_{16}} + h_{16}$$

$$S_{17} = S_{18}$$

$$X_{18} = \frac{S_{18} - S_{f18}}{S_{fg18}} \quad \text{(if applicable)}$$

$$_{17}W_{18} > m_{16}\,(h_{17} - h_{18})$$

The r e s u l t s of all computations are included in a number of tables. Tables 3 to 8 are similar. Each table is for a given amount of superheating $_5Q_6$, and the relation between flash tank pressure and steam turbine power output can be readily observed.

$P_9 = 200$ psia

$T_9 = 280°F$

$h_9 = 249.06\ Btu/lbm$

$\dot{m}_9 = 292000\ \frac{lbm}{hr}$

$P_{18} = 8$ psia

$s_{f18} = 0.2674\ \frac{Btu}{lbm\text{-}°R}$

$s_{fg_{18}} = 1.5383\ \frac{Btu}{lbm\text{-}°R}$

$h_{f18} = 150.79\ \frac{Btu}{lbm}$

$h_{fg_{18}} = 988.5\ \frac{Btu}{lbm}$

P_{10} (psia)	45	40	35	30	25	20	15
x_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
s_{17} (Btu/lbm-°R)	1.6669	1.6763	1.6870	1.6993	1.7139	1.7319	1.7549
T_{17} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
x_{18} or T_{18}	0.9098	0.9159	0.9228	0.9308	0.9403	0.9520	0.9670
h_{18} (Btu/lbm)	1050.1	1056.2	1063.0	1070.9	1080.3	1091.8	1106.7
${}_{17}\dot{W}_{18}$ (Btu/hr)	218,552	462,662	684,545	870,589	1,000,779	1,037,741	902,286

Table 3 Single Flash System, for ${}_5Q_6 = 0$

19

$P_9 = 200$ psia

$T_9 = 280\ °F$

$h_9 = 249.06\ \frac{Btu}{lbm}$

$\dot{m}_9 = 292000\ \frac{lbm}{hr}$

$P_{18} = 8$ psia

$s_{f18} = 0.2674\ \frac{Btu}{lbm\text{-}°R}$

$s_{fg18} = 1.5383\ \frac{Btu}{lbm\text{-}°R}$

$h_{f18} = 150.79\ \frac{Btu}{lbm}$

$h_{fg18} = 988.5\ \frac{Btu}{lbm}$

P_{10} (psia)	45	40	35	30	25	20	15
x_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1292.4	1222.7	1199.9	1187.2	1177.9	1169.7	1161.3
s_{17} (Btu/lbm-°R)	1.8089	1.7445	1.7307	1.7308	1.7381	1.7510	1.7702
T_{17} (°F)	516.7	371.8	323.6	295.8	274.5	254.9	234.3
x_{18} or T_{18}	1.00	0.9602	0.9512	0.9513	0.9561	0.9644	0.9769
h_{18} (Btu/lbm)	1139.2	1099.9	1091.1	1091.2	1095.9	1104.1	1116.5
${}_{17}\dot{W}_{18}$ (Btu/hr)	274,670	500,570	715,450	896,740	1,021,970	1,055,440	916,610

Table 4 Single Flash System, for ${}_5Q_6$ = 215,850 Btu/hr

20

$P_9 = 200$ psia
$T_9 = 280\,°F$
$h_9 = 249.06\ \frac{Btu}{lbm}$
$\dot{m}_9 = 292000\ \frac{lbm}{hr}$

$P_{18} = 8$ psia
$S_{f18} = 0.2674\ \frac{Btu}{lbm\text{-}°R}$
$S_{fg18} = 1.5383\ \frac{Btu}{lbm\text{-}°R}$
$h_{f18} = 150.79\ \frac{Btu}{lbm}$
$h_{fg18} = 988.5\ \frac{Btu}{lbm}$

P_{10} (psia)	45	40	35	30	25	20	15
x_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1412.8	1275.6	1232.7	1210.3	1195.2	1183.1	1171.9
S_{17} (Btu/lbm-°R)	1.9188	1.8038	1.7708	1.7605	1.7611	1.7694	1.7832
T_{17} (°F)	763.1	480.0	390.7	342.9	309.7	282.3	256.3
x_{18} or T_{18}	358.1°	0.9988	0.9773	0.9706	0.9710	0.9764	0.9854
h_{18} (Btu/lbm)	1221.3	1138.1	1116.9	1110.2	1110.6	1116.0	1124.9
${}_{17}\dot{W}_{18}$ (Btu/hr)	343,340	560,490	761,480	935,040	1,054,370	1,079,570	961,620

Table 5 Single Flash System, for ${}_5Q_6$ = 431,700 Btu/hr

21

$P_9 = 200$ psia

$T_9 = 280°F$

$h_9 = 249.06 \frac{Btu}{lbm}$

$\dot{m}_9 = 292000 \frac{lbm}{hr}$

$T_{5_{max}} = 915°F$

$P_{18} = 8$ psia

$S_{f18} = 0.2674 \frac{Btu}{lbm\text{-}°R}$

$S_{fg18} = 1.5383 \frac{Btu}{lbm\text{-}°R}$

$h_{f18} = 150.79 \frac{Btu}{lbm}$

$h_{fg18} = 988.5 \frac{Btu}{lbm}$

P_{10} (psia)	45	40	35	30	25	20	15
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1489.0 (max)	1328.6	1265.6	1229.3	1212.6	1196.5	1182.4
S_{17} (Btu/lbm-°R)	1.9773 (max)	1.8576	1.8081	1.7836	1.7833	1.7871	1.7999
T_{17} (°F)	915° (max)	590.7	459.0	382.1	345.8	310.2	278.3
X_{18} or T_{18}	467.4°	257.3	186.1	0.9856	0.9854	0.9879	0.9962
h_{18} (Btu/lbm)	1272.4	1174.4	1140.8	1125.1	1124.9	1127.3	1135.5
${}_{17}\dot{W}_{18}$ (Btu/hr)	388,340 (max)	628,570	820,670	973,340	1,093,010	1,113,360	959,570

Table 6 Single Flash System, for ${}_5Q_6$ = 647,550 Btu/hr

$P_9 = 200$ psia

$T_9 = 280°F$

$h_9 = 249.06 \frac{Btu}{lbm}$

$\dot{m}_9 = 292000 \frac{lbm}{hr}$

$T_{5max} = 915°$

$P_{18} = 8$ psia

$s_{f18} = 0.2674 \frac{Btu}{lbm-°R}$

$s_{fg18} = 1.5383 \frac{Btu}{lbm-°R}$

$h_{f18} = 150.79 \frac{Btu}{lbm}$

$h_{fg18} = 988.5 \frac{Btu}{lbm}$

P_{10} (psia)	45	40	35	30	25	20	15
x_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1489.0 (max)	1381.5	1298.4	1256.5	1229.9	1210.0	1193.0
s_{17} (Btu/lbm-°R)	1.9773 (max)	1.9058	1.8425	1.8149	1.8043	1.8043	1.8139
T_{17} (°F)	915 (max)	700	527.3	438.9	381.9	338.3	300.4
x_{18} or T_{18}	467.4° (max)	335.6°	234.6°	195.3°	0.9991	0.9991	193.9°
h_{18} (Btu/lbm)	1272.4 (max)	1210.9	1163.8	1145.2	1138.4	1138.4	1144.6
${}_{17}\dot{W}_{18}$ (Btu/hr)	388,340 (max)	695,420	885,110	1,039,660	1,140,370	1,151,970	990,260

Table 7 Single Flash System, for ${}_5Q_6$ = 863,400 Btu/hr

23

$P_9 = 200$ psia
$T_9 = 280\ °F$
$h_9 = 249.06\ \frac{Btu}{lbm}$
$\dot{m}_9 = 292000\ \frac{lbm}{hr}$

$T_{5_{max}} = 915\ °F$

$P_{18} = 8$ psia
$s_{f18} = 0.2674\ \frac{Btu}{lbm\text{-}°R}$
$s_{fg18} = 1.5383\ \frac{Btu}{lbm\text{-}°R}$
$h_{f18} = 150.79\ \frac{Btu}{lbm}$
$h_{fg18} = 988.5\ \frac{Btu}{lbm}$

P_{10} (psia)	45	40	35	30	25	20	15
x_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1489.0 (max)	1434.5	1331.2	1279.6	1247.2	1223.4	1203.5
s_{17} (Btu/lbm-°R)	1.9773 (max)	1.9491	1.8746	1.8399	1.8244	1.8208	1.8275
T_{17} (°F)	915 (max)	806.4	595.3	487.2	418.1	366.6	322.7
x_{18} or T_{18}	467.4° (max)	413.1°	284.0°	230.8°	208.5°	203.4°	212.9°
h_{18} (Btu/lbm)	1272.4 (max)	1246.9	1186.9	1162.0	1151.5	1149.1	1153.6
${}_{17}\dot{W}_{18}$ (Btu/hr)	388,340 (max)	764,720	948,890	1,098,510	1,192,710	1,195,410	1,020,950

Table 8 Single Flash System, for ${}_5Q_6$ = 1,079,250 Btu/hr

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Table 9 shows the maximum power outputs at different flash tank pressures with the maximum amount of superheating. Tables 10 and 11 show the effect of superheating $_5Q_6$ at optimal flashing conditions. Discussion of the results in these tables is included in the next section.

4.4 Discussion of results

For the case of no superheating, $_5Q_6$, there is a maximum turbine power output with respect to a specific flash tank pressure as indicated in Table 3. Similar observations are obtained in Table 4 to Table 8 when various amount of superheating $_5Q_6$ are specified. This fact can also be noticed by the curves in Fig. 8. Furthermore, from the tables or Fig. 8, we observed that the maximum turbine power output occurred more or less at a flash tank pressure of 20 psia (corresponding a flash tank temperature of 228.0 ^oF). This is regardless of the amount of superheating $_5Q_6$ involved. According to Equ. (8), the optimal flash tank temperature is the arithmetic mean of brine temperature at section (8) (280^oF) and the steam temperature at condenser (182.9^oF), which is 231.5^oF. As we can see, this represents a very good agreement between Equ. (8) and the numerical computations. In fact, if we consider the flash tank pressure to be 21 psia, we will get even closer agreement. The amount of superheating $_5Q_6$ allowed is mainly determined by the mass flow rate of steam, the temperature of exhaust gas from the gas engine, and of course the design of superheater. If the assumed maximum temperature of 915^oF is maintained for steam leaving the superheater, the $_5Q_6$ in this situation should depend

$P_9 = 200$ psia
$T_9 = 280\ °F$
$h_9 = 249.06\ \frac{Btu}{lbm}$
$\dot{m}_9 = 292{,}000\ \frac{lbm}{hr}$

$T_5 = 915°F$
$T_{17} = 915°F$

$P_{18} = 8$ psia

P_{10} (psia)	45	40	35	30	25	20	15
x_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510	0.07007
T_{10} (°F)	274.44	267.25	259.28	250.33	240.07	227.96	213.03
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089	20460
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3	1150.8
h_{17} (Btu/lbm)	1489.0	1489.1	1489.3	1489.4	1489.5	1489.7	1489.9
${}_5\dot{Q}_{6\,max}$ (Btu/hr)	568,340	1,301,980	2,118,740	3,038,650	4,099,080	5,364,070	6,937,990
s_{17} (Btu/lbm-°R)	1.9773	1.9904	2.0052	2.0223	2.0425	2.0672	2.0990
T_{18} (°F)	467.4	493.6	524.6	560.9	604.1	660.9	736.5
h_{18} (Btu/lbm)	1272.4	1284.7	1299.4	1316.6	1337.2	1364.6	1401.4
${}_{17}\dot{W}_{18\,max}$ (Btu/hr)	388,340	833,200	1,248,750	1,614,140	1,898,120	2,012,730	1,810,710
${}_{17}\dot{W}_{18} / {}_5\dot{Q}_6$	0.6833	0.6399	0.5894	0.5312	0.4631	0.3752	0.2610
$\frac{{}_{17}\dot{W}_{18\,max} - {}_{17}\dot{W}_{18\,\dot{Q}=0}}{{}_5\dot{Q}_{6\,max}}$	0.2987	0.2846	0.2663	0.2447	0.2189	0.1818	0.1309

Table 9 Single Flash System - Maximum Power Output at Various Flashing Pressures

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${}_5\dot{Q}_6$ ($\frac{Btu}{hr}$)	T_{17} (°F)	X_{18} or T_{18}	${}_{17}\dot{W}_{18}$ (kw)
0	228	0.952	304
216,000	255	0.964	309
432,000	282	0.976	316
648,000	310	0.988	326
863,000	338	0.999	338
1,079,000	366	203 °F	350

Table 10 Single Flash System Operates at Optimal Flash Condition

$_5\dot{Q}_6$	$\Delta_{17}\dot{W}_{18} = {_{17}\dot{W}_{18}} - ({_{17}\dot{W}_{18}})_{\dot{Q}=0}$	$\frac{\Delta_{17}\dot{W}_{18}}{({_{17}\dot{W}_{18}})_{\dot{Q}=0}} \times 100$	$\frac{\Delta_{17}\dot{W}_{18}}{_5\dot{Q}_6} \times 100$
0	0	0	—
215,850	17,700	1.71	8.20
431,700	41,830	4.03	9.69
647,550	75,620	7.29	11.68
863,400	114,230	11.01	13.23
1,079,250	157,670	15.19	14.61
5,364,070 max	974,990	93.95	18.18

Table 11 Single Flash System - Superheating and Power Output at Optimal Flashing Condition

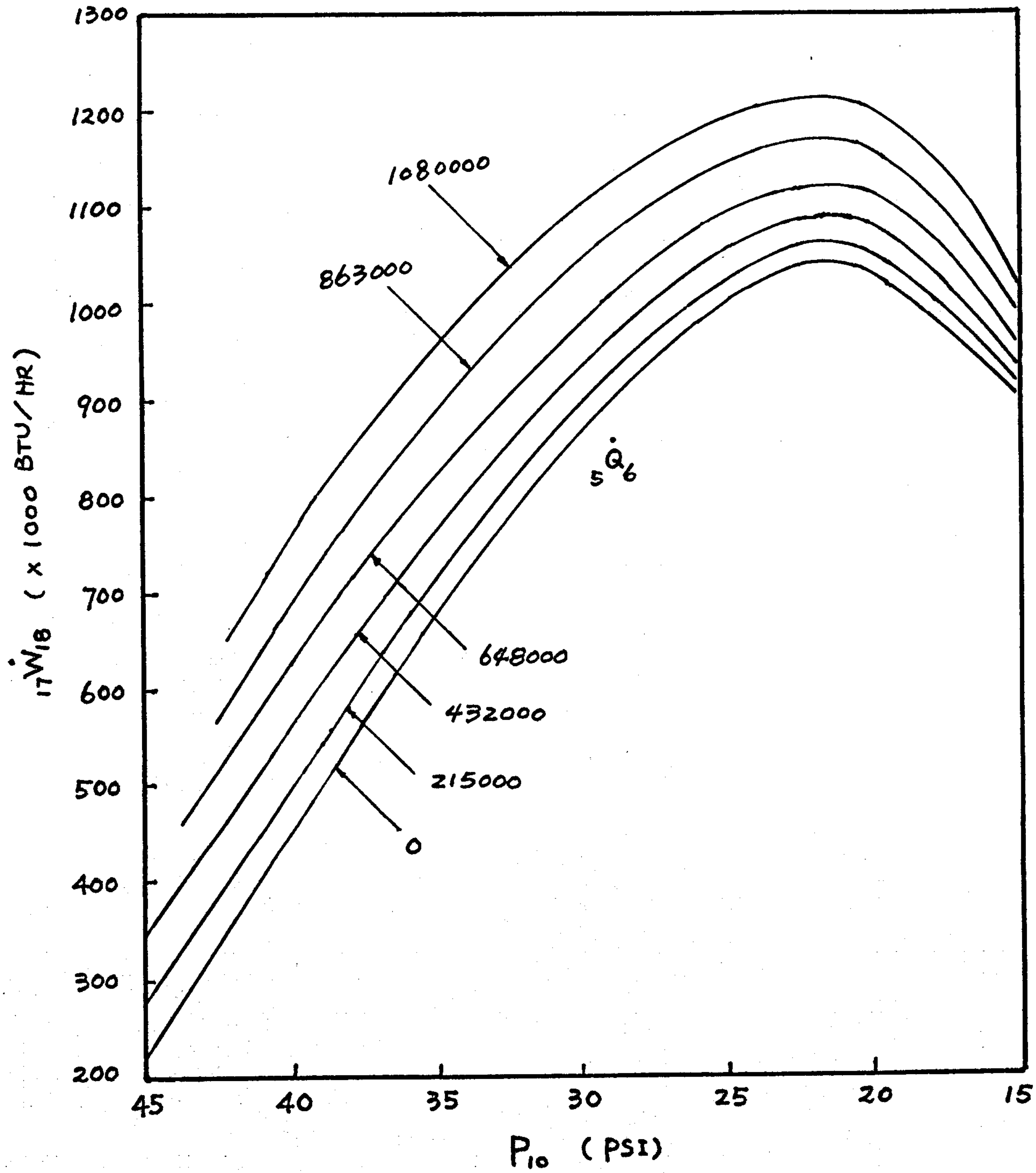


Fig. 8 Single Flash System - $_{17}\dot{W}_{18}$ v.s. P_{10}

on the flash tank condition as indicated in Table 9. The lower the flash tank pressure, the higher the mass flow rate of steam, and the higher the magnitude of $_5Q_6$. In Table 9, the highest power output $_{17}W_{18}$ still occurs at the same optimal condition (about 20 psia), even though the superheating involved is not the highest. This means the optimal flashing condition is independent of the amount the superheating involved as stated earlier. At the optimal flashing condition, the turbine power output $_{17}W_{18}$ is increased as the amount of superheating $_5Q_6$ is increased. This is is shown in Fig. 9. The effect of superheating $_5Q_6$ to the power output $_{17}W_{18}$ is further explained in Table 10. In the table, the ratio of power output increase $_{17}W_{18}$ due to superheating of the power output ($_{17}W_{18}$) vs. $_5Q_6 = 0$ without superheating is computed. The relation between this ratio and $_5Q_6$ is plotted in Fig. 10. Similarly, the ratio of power output increase versus $_5Q_6$ in Table 10 is plotted in Fig. 11.

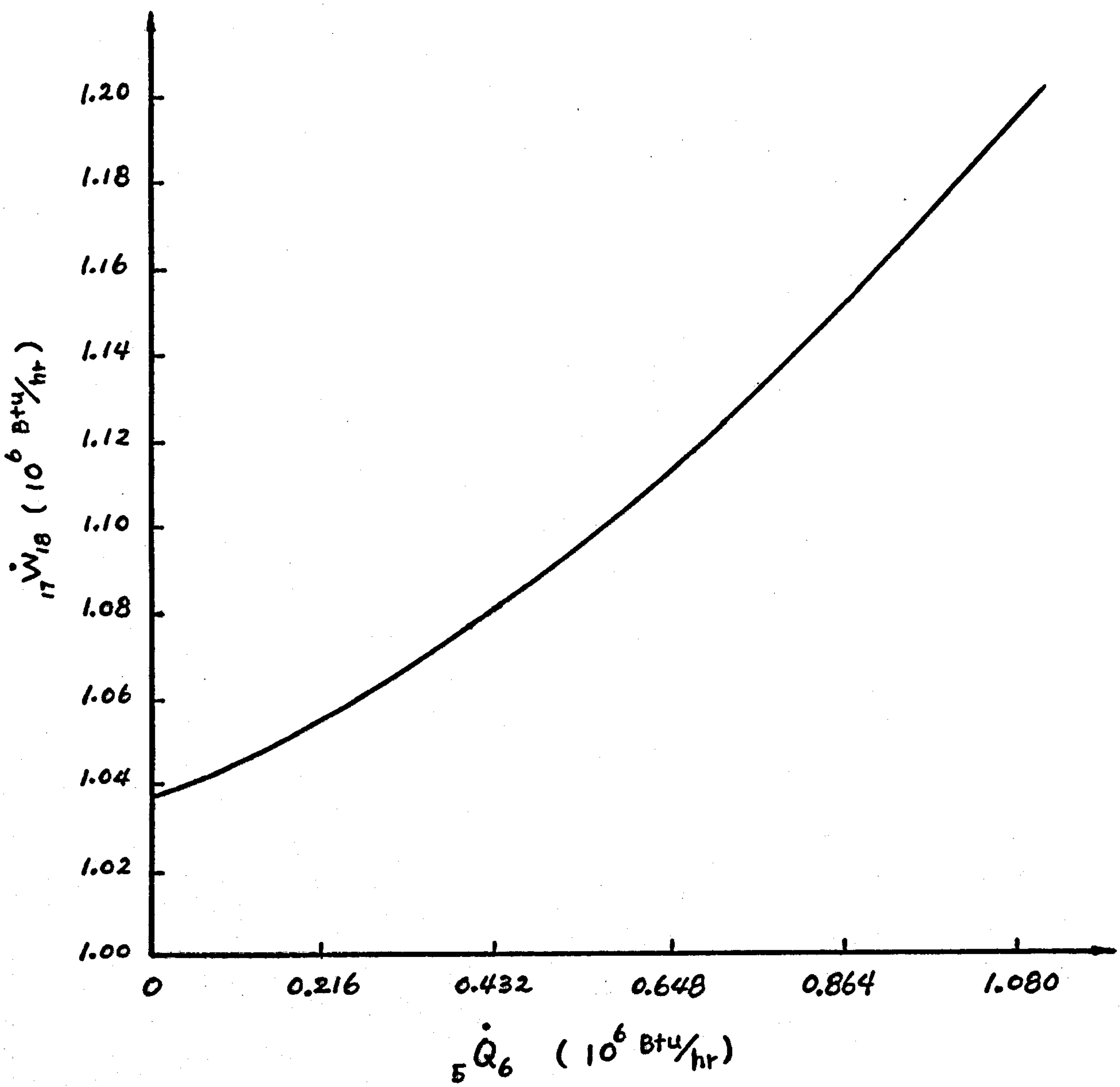


Fig. 9 Single Flash System - $_{17}\dot{W}_{18}$ v.s. $_5\dot{Q}_6$ at Optimal Flashing Condition

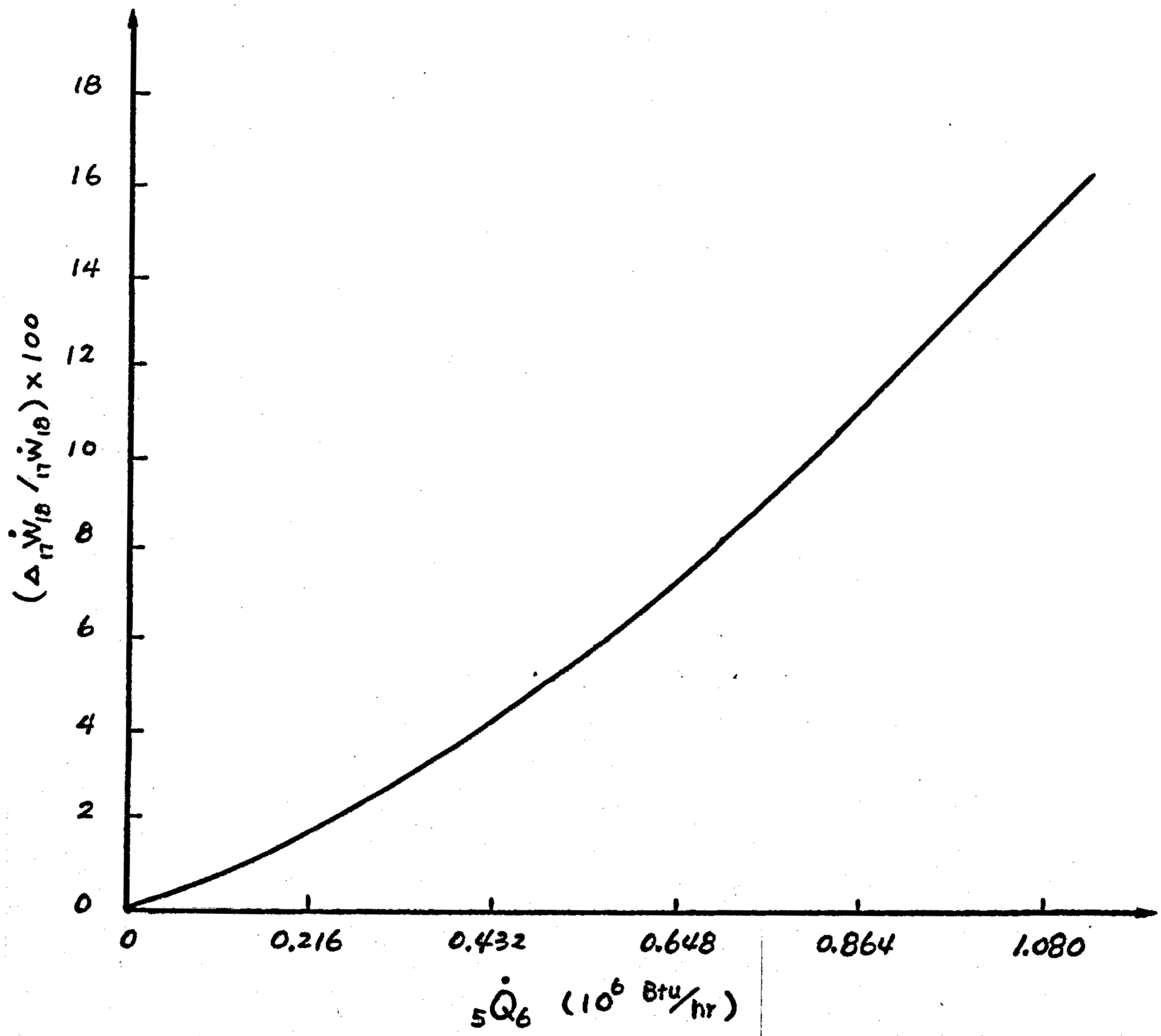


Fig. 10 Single Flash System - $\Delta_{17}\dot{W}_{18}/_{17}\dot{W}_{18}$ | Q = 0 v.s. $_5\dot{Q}_6$ at Optimal Flashing Condition

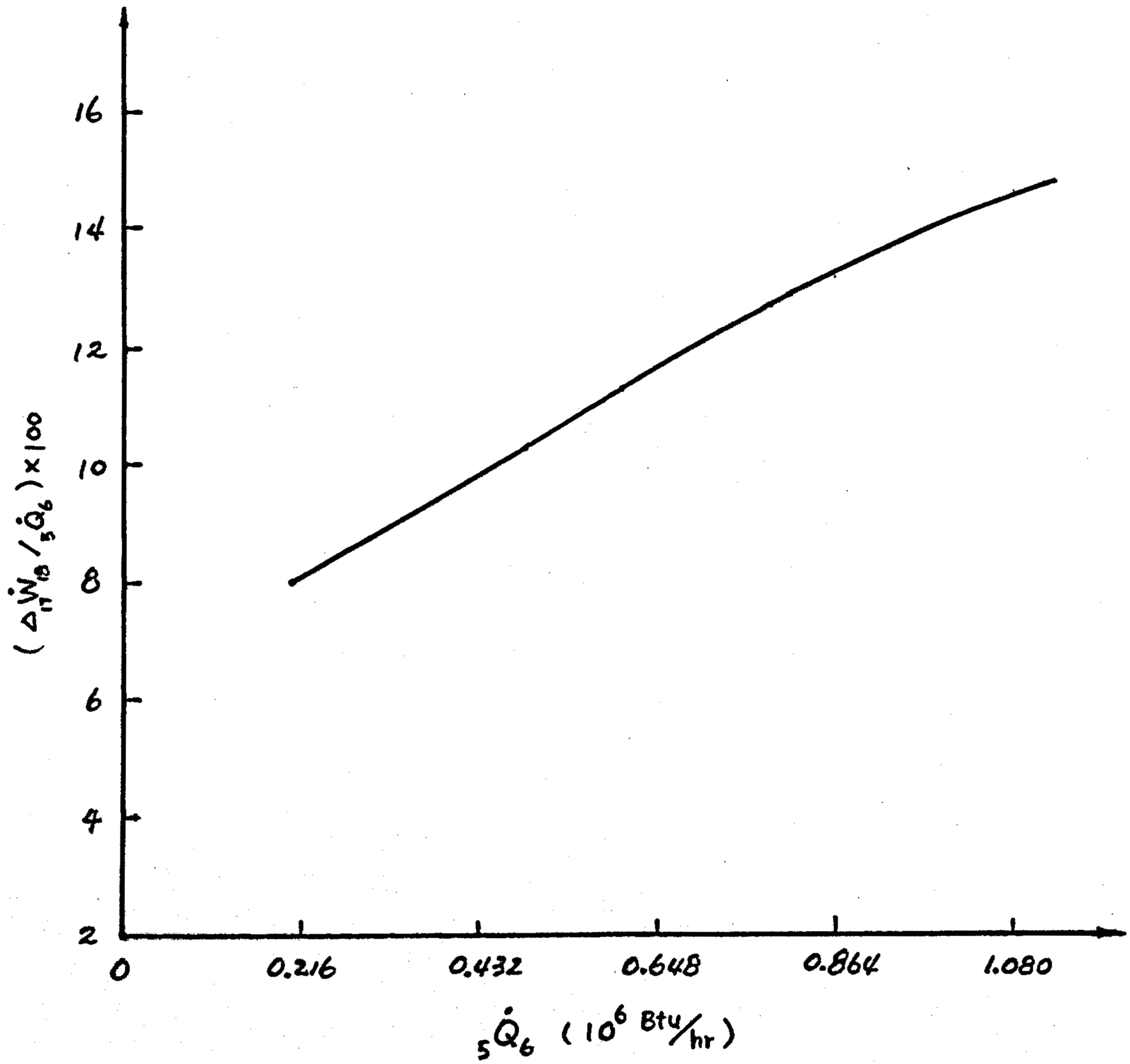


Fig. 11 Single Flash System - $\Delta_{17}\dot{W}_{18}/_5\dot{Q}_6$ at Optimal Flashing Condition

Chapter 5

Gas Engine Topped Double-Flash System

5.1 Double Flash System

From the second law of thermodynamics, the higher the temperature at which the heat is transferred to the system, the higher the thermal efficiency of the system. Therefore, to better use the exhaust heat from the gas engine, only a proper amount of steam from one flashing process should be sent to receive exhaust heat at the steam superheater, and more steam is generated from further flashing to produce additional power. This way, the exhaust heat is transferred to the system at higher temperature.

A double flash system can be used to serve this purpose. Shown in Fig. 12 is a schematic diagram of a double flash system. There are two flash tanks as well as two steam turbines. Only the steam from the higher pressure tank goes to the superheater, steam from the lower flash tank goes to the low pressure steam turbine directly. For a given flow condition of brine entering the high pressure expansion valve and for a fixed pressure at the steam condenser, optimal flashing conditions at both flash tanks should exist. This is similiar to the situation in the single flash tank. The optimal conditions will be determined in the next section.

5.2 Optimal Flashing Conditions

With reference to Figure 12, brine at temperature T_a enters the high pressure expansion valve with a mass flow rate m_A. The steam inside the condenser is maintained at constant pressure P_G and with a corresponding saturation temperature T_G. The mass

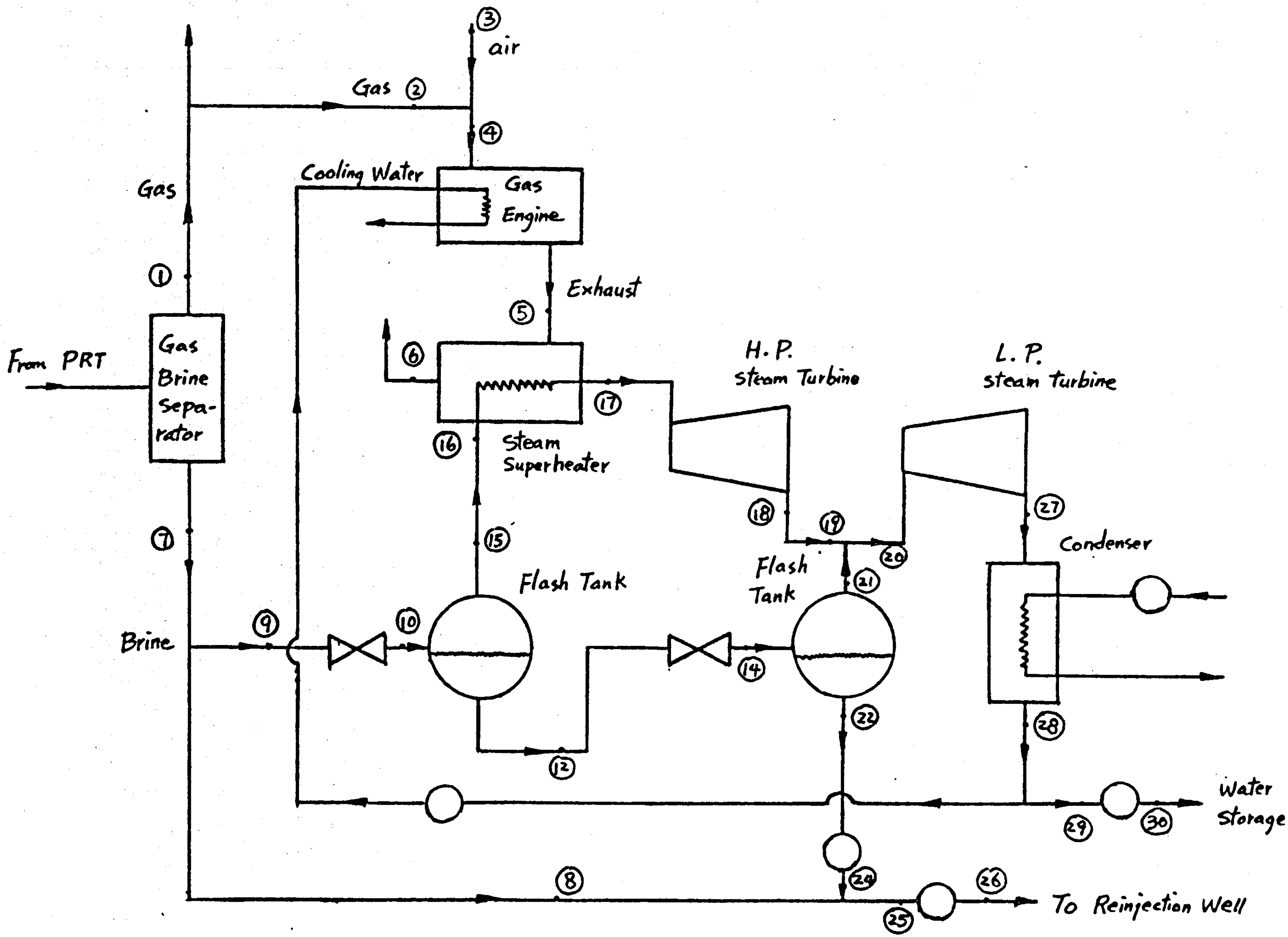


Fig. 12 Flow Diagram of a Gas Engine Topped Double Flash System

flow rate of brine entering the low pressure expansion valve is almost equal to M_A because the quality of steam in the flash tank is very low. Therefore, for an arbitarily given temperature T_B at flash tank B, there exists an optimal temperature at flash tank E. According to the analysis of single flash system, this optimal temperature T_E is

$$T_E = \frac{T_B + T_G}{2} \qquad (10)$$

Similarly,, if an arbitarily given temperature T_E is maintained at flash tank E, the optimal condition at flash tank B is given by the flash tank temperature T_B

$$T_B = \frac{T_A + T_E}{2} \qquad (11)$$

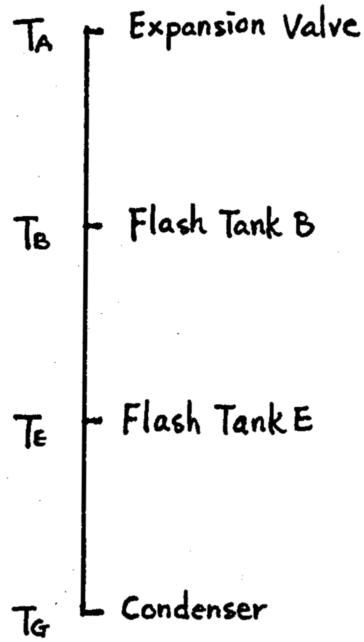
Solving for T_B and T_E from Equ. (10) and Equ. (11)

$$T_B = \frac{2T_A + T_G}{3} = T_A = \frac{(T_A - T_G)}{3} \qquad (12)$$

$$T_E = \frac{T_A + 2\ T_G}{3} = T_A - \frac{2(T_A - T_G)}{3} \qquad (13)$$

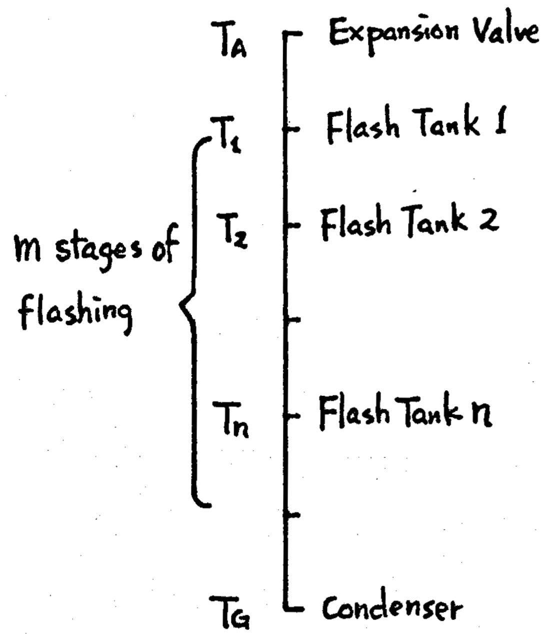
For a double flash system operating at maximum power output, the high and low pressure tank temperatures should be computed by Equ. (12) and Equ. (13).

From Equations (12) and (13) and as shown graphically in Figure 13, the temperature difference between two positions are all the same if these positions are in the following order, high pressure



$$T_B = T_A - \frac{(T_A - T_G)}{3}$$

$$T_E = T_A - \frac{2(T_A - T_G)}{3}$$



$$T_n = T_A - \frac{n(T_A - T_G)}{m+1}$$

Fig. 13 Double Flash or Multiple Flash System - Temperatures of Flash Tanks for Maximum System Power Output expansion valve, first high pressure flash tank, second high pressure flash tank, etc, and steam condenser. So if more than two stages of flashing is involved, the optimal flashing condition can be readily obtained. For example, for the n th flash tank in an m stage flashing system, the optimal temperature inside the tank is given by the equation

$$T_n = T_A - \frac{n(T_A - T_G)}{m + 1} \qquad (14)$$

Similarly, as in the single flash system, the optimal flashing condition is more or less independent of the amount of superheating involved.

The conclusions in this section will be checked with the numerical computations in the next section.

5.3 Thermodynamic Analysis of a Gas Engine Topped Double Flash System

Similiar to the analysis of the single flash system, the data from the EPRI system is used here for the numerical computations.

A flow diagram with section labels is shown in Figure 14 which is derived from Figure 13. As in the single flash system analysis, the main purpose of our analysis is to obtain net power outputs of the system under various operational conditions.

From Figure 14, brine enters the high pressure expansion valve at section (9) with a constant flow rate of 292000 lbm/hr. The temperature of the brine is at 280°F. For a given amount of

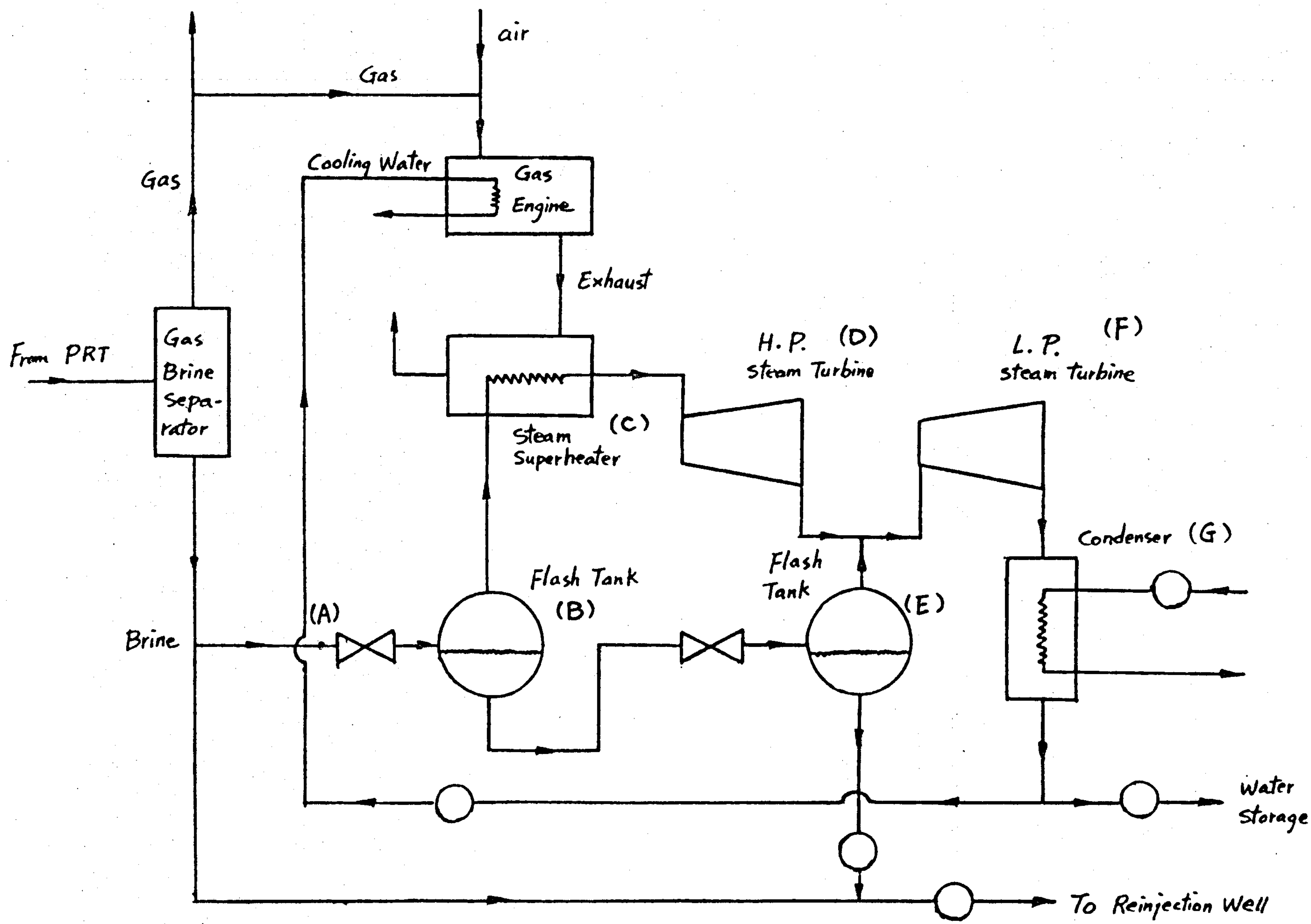


Fig. 14 Flow Diagram of a Gas Engine Topped Double Flash System with section Numbers

exhaust heat ${}_5Q_6$, if the pressure at the high flash tank is arbitrarily chosen (for example, the first value is 45 psia), from Equ. (8) of single flash system (or Equ. (10) in this chapter), the optimal condition of the low pressure flash tank can be determined. Then both the high pressure turbine and the low pressure turbine power outputs can be computed in order to obtain the total power output of the system. We then vary the pressure at the high pressure flash tank (for example, decrease the pressure by 5 psia), and repeat the above computations to obtain a new total turbine output of the system. Continuing this kind of computations, we are able to obtain a relation between total power outputs of the system and the pressure at the high pressure flash tank. From this relation, the optimal flashing condition at the high pressure flash tank can be obtained. This result should be compared with theoretical estimation in the last section. The above analysis should be repeated for different amount of eexhaust heat ${}_5Q_6$ transferred to the steam superheater.

As in the single flash system analysis, ideal thermodynamic processes are assumed for all computations. The following equations are used.

$$X10 = \frac{249.06 - h_{f10}}{h_{fg10}}$$

$$M_{16} = X_{10} (M_q)$$

$$T_{10} = T_{16}$$

$$h_{17} = \frac{5Q6}{M16} + h_{16}$$

$$S_{17} = S_{18}$$

$$T_{18} = \frac{T_{10} + 182.86}{2}$$

$$X_{18} = \frac{S_{18} - S_{f18}}{S_{fg18}} \quad \text{(if applicable)} \qquad (15)$$

$${}_{17}W_{18} = M_{16}\,(h_{17} - h_{18})$$

$$X_{14} = \frac{h_{12} - h_{f14}}{h_{fg14}}$$

$$M_{21} = X_{14}\,(Mq)$$

$$M_{19} = M_{16}$$

$$M_{20} = M_{21} + M_{19}$$

$$h_{20} = \frac{M_{19}\,h_{19} + M_{21}\,h_{21}}{M_{20}}$$

$$S_{20} = S_{27}$$

$$X_{27} = \frac{S_{27} - S_{f27}}{S_{fg27}} \quad \text{(if applicable)}$$

$$h_{27} = 150.79 + X_{27}\,(988.5)$$

$${}_{20}W_{27} = M_{20}\,(h_{20} - h_{27})$$

$W_{tot} = {}_{17}W_{18} + {}_{20}W_{27}$

The results of computations are listed in a number of tables, Table 12 to Table 17 are similiar, each table is for a given amount of superheating ${}_5Q_6$, and the relation between the pressure at the high flash tank and the total steam turbine output can be easily observed. Discussion of the results in these tables is given in the next section.

5.4 Discussion of Results

For the case of no superheating, ${}_5Q_6 = 0$, there is a maximum total turbine power output with respect to a particular high-pressure flash tank pressure as indicated in Table 12. Similiar observations are obtained in Table 13 to Table 17 when various amount of superheating ${}_5Q_6$ are specified. This fact can be noticed graphically by the curves in Fig. 15. From Fig. 15 or the tables mentioned, we noticed that the maximum total turbine power output occurred more or less at a high-pressure flash tank tank pressure of 30 psia (corresponding to a high pressure flash tank temperature of 250.3°F). This is independent of the amount of superheating ${}_5Q_6$ involved. According to Equ. (12), the optimal high pressure flash tank temperature should be 247.6°F. As we can see, this represents a very good agreement between the result from Equ. (12) and the numerical computations from the tables. In fact, if we consider the high pressure flash tank pressure is 28 psia, we will get even closer agreement. The optimal condition at the low pressure flash tank observed from the tables should match Equ. (13) automatically if high pressure flash tank condition matchs Equ. (12). This is because the

$P_9 = 200$ psia
$T_9 = 280°F$
$\dot{m}_9 = 292000$ lbm/hr

$T_5 = 915°F$
$P_{27} = 8$ psia

P_{10} (psia)	45	40	35	30	25	20
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
h_{17} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
S_{17} ($\frac{Btu}{lbm\text{-}°R}$)	1.6669	1.6763	1.6870	1.6993	1.7139	1.7319
T_{17} (°F)	274.44	267.25	259.28	250.33	240.07	227.96
P_{18} (psia)	20.26	18.92	17.52	16.09	14.54	12.88
h_{18} ($\frac{Btu}{lbm}$)	1112.5	1114.4	1115.9	1118.3	1120.9	1124.5
${}_{17}\dot{W}_{18}$ ($\frac{Btu}{hr}$)	106,672	225,421	336,683	427,821	494,781	511,630
X_{14}	0.04848	0.04452	0.04028	0.03527	0.02977	0.02331
$\dot{m}_{20}$ (lbm/hr)	15780	16721	17816	18984	20410	22131
h_{20} (Btu/lbm)	1165.5	1155.4	1153.6	1152.1	1150.1	1148.0
S_{20} ($\frac{Btu}{lbm\text{-}°R}$)	1.7308	1.7361	1.7426	1.7492	1.7574	1.7673
h_{27} ($\frac{Btu}{lbm}$)	1091.2	1094.6	1098.8	1103.0	1108.3	1114.6
${}_{20}\dot{W}_{27}$ ($\frac{Btu}{hr}$)	1,030,434	1,016,637	976,317	932,114	853,138	739,175
$\dot{W}_{tot}$ ($\frac{Btu}{hr}$)	1,137,110	1,242,060	1,313,000	1,359,940	1,347,920	1,250,810

Table 12 Double Flash System for ${}_5Q_6 = 0$

$P_9 = 200$ psia
$T_9 = 280$ °F
$\dot{m}_9 = 292000 \frac{lbm}{hr}$

$T_5 = 915$ °F
$P_{27} = 8$ psia

P_{10} (psia)	45	40	35	30	25	20
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
h_{17} (Btu/lbm)	1292.4	1222.7	1199.9	1187.2	1177.9	1169.7
S_{17} ($\frac{Btu}{lbm\text{-}°R}$)	1.8089	1.7445	1.7307	1.7308	1.7381	1.7510
T_{17} (°F)	516.7	371.8	323.6	295.8	274.5	254.9
P_{18} (psia)	20.26	18.92	17.52	16.09	14.54	12.88
h_{18} ($\frac{Btu}{lbm}$)	1214.8	1160.9	1145.5	1139.6	1137.2	1137.2
${}_{17}\dot{W}_{18}$ ($\frac{Btu}{hr}$)	139,127	251,917	357,726	444,635	507,244	522,893
X_{14}	0.04848	0.04452	0.04028	0.03527	0.02977	0.02331
$\dot{m}_{20}$ ($\frac{lbm}{hr}$)	15862	16894	18018	19190	20619	22341
h_{20} ($\frac{Btu}{lbm}$)	1163.1	1156.7	1153.6	1152.1	1150.1	1148.0
S_{20} ($\frac{Btu}{lbm\text{-}°R}$)	1.7403	1.7385	1.7426	1.7492	1.7574	1.7673
h_{27} ($\frac{Btu}{lbm}$)	1097.3	1096.1	1098.8	1103.0	1108.3	1114.6
${}_{20}\dot{W}_{27}$ ($\frac{Btu}{hr}$)	1,043,720	1,023,776	987,386	942,229	861,874	746,189
$\dot{W}_{tot}$ ($\frac{Btu}{hr}$)	1,182,850	1,275,690	1,345,110	1,386,860	1,369,120	1,269,080

Table 13 Double Flash System for ${}_5Q_6$ = 215,850 Btu/hr

$P_9 = 200$ psia $T_5 = 915\,°F$

$T_9 = 280\,°F$ $P_{27} = 8$ psia

$\dot{m}_9 = 292000\ \frac{lbm}{hr}$

P_{10} (psia)	45	40	35	30	25	20
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089
h_{16} $(\frac{Btu}{lbm})$	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
h_{17} $(\frac{Btu}{lbm})$	1412.8	1275.6	1232.7	1210.3	1195.2	1183.1
S_{17} $(\frac{Btu}{lbm\text{-}°R})$	1.9188	1.8038	1.7708	1.7605	1.7611	1.7694
T_{17} (°F)	763.1	480.0	390.7	342.9	309.7	282.3
P_{18} (psia)	20.26	18.92	17.52	16.09	14.54	12.88
h_{18} $(\frac{Btu}{lbm})$	1314.8	1204.7	1173.5	1159.8	1152.6	1149.3
${}_{17}\dot{W}_{18}$ $(\frac{Btu}{hr})$	175,702	289,011	389,290	471,725	530,924	543,808
X_{14}	0.04848	0.04452	0.04028	0.03527	0.02977	0.02331
$\dot{m}_{20}$ (lbm/hr)	15862	16894	18073	19310	20785	22520
h_{20} $(\frac{Btu}{lbm})$	1174.4	1167.3	1160.8	1155.8	1151.6	1148.9
S_{20} $(\frac{Btu}{lbm\text{-}°R})$	1.7562	1.7537	1.7528	1.7547	1.7596	1.7688
h_{27} $(\frac{Btu}{lbm})$	1107.5	1105.9	1105.3	1106.5	1109.6	1115.6
${}_{20}\dot{W}_{27}$ $(\frac{Btu}{hr})$	1,061,168	1,037,292	1,003,052	951,983	872,970	749,916
$\dot{W}_{tot}$ $(\frac{Btu}{hr})$	1,236,870	1,326,300	1,392,340	1,423,710	1,403,890	1,293,720

Table 14 Double Flash System for ${}_5Q_6$ = 431,700 Btu/hr

$P_9 = 200$ psia

$T_9 = 280\ °F$

$\dot{m}_9 = 292000\ lbm/hr$

$T_5 = 915\ °F$

$P_{27} = 8$ psia

P_{10} (psia)	45	40	35	30	25	20
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
h_{17} (Btu/lbm)	1489.0 max	1328.6	1265.6	1229.3	1212.6	1196.5
S_{17} (Btu/lbm-°R)	1.9773 max	1.8576	1.8081	1.7836	1.7833	1.7871
T_{17} (°F)	915 max	590.7	459.0	382.1	345.8	310.2
P_{18} (psia)	20.26	18.92	17.52	16.09	14.54	12.88
h_{18} (Btu/lbm)	1378.2 max	1249.5	1201.5	1176.2	1168.0	1161.4
${}_{17}\dot{W}_{18}$ (Btu/hr)	198,651 max	322,437	421,511	496,011	555,850	564,724
X_{14}	0.04848	0.04452	0.04028	0.03527	0.02977	0.02331
$\dot{m}_{20}$ (lbm/hr)	15862	16894	18073	19310	20785	22520
h_{20} (Btu/lbm)	1181.6	1175.1	1171.0	1163.8	1160.8	1157.6
S_{20} (Btu/lbm-°R)	1.7660 max	1.7646	1.7673	1.7662	1.7730	1.7815
h_{27} (Btu/lbm)	1113.8	1112.9	1114.6	1113.9	1118.3	1123.7
${}_{20}\dot{W}_{27}$ (Btu/hr)	1,075,444	1,050,807	1,019,317	963,569	883,363	763,428
$\dot{W}_{tot}$ (Btu/hr)	1,274,090 max	1,373,240	1,440,830	1,459,580	1,439,210	1,328,150

Table 15 Double Flash System for ${}_5Q_6$ = 647,550 Btu/hr

$P_9 = 200$ psia
$T_9 = 280$ °F
$\dot{m}_9 = 292000$ lbm/hr

$T_5 = 915$ °F
$P_{27} = 8$ psia

P_{10} (psia)	45	40	35	30	25	20
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
h_{17} (Btu/lbm)	1489.0	1381.5	1298.4	1256.5	1229.9	1210.0
S_{17} (Btu/lbm-°R)	1.9773	1.9058	1.8425	1.8149	1.8043	1.8043
T_{17} (°F)	915	700	527.3	438.9	381.9	338.3
P_{18} (psia)	20.26	18.92	17.52	16.09	14.54	12.88
h_{18} (Btu/lbm)	1378.2	1294.4	1229.3	1199.6	1181.9	1173.5
$_{17}\dot{W}_{18}$ (Btu/hr)	198,651	355,047	454,391	531,507	598,224	587,249
X_{14}	0.04848	0.04452	0.04028	0.03527	0.02977	0.02331
$\dot{m}_{20}$ (lbm/hr)	15862	16894	18073	19310	20785	22520
h_{20} (Btu/lbm)	1181.6	1185.9	1181.1	1175.1	1169.2	1166.2
S_{20} (Btu/lbm-°R)	1.7660	1.7792	1.7812	1.7821	1.7850	1.7940
h_{27} (Btu/lbm)	1113.8	1122.3	1123.6	1124.2	1125.9	1131.8
$_{20}\dot{W}_{27}$ (Btu/hr)	1,075,444	1,074,458	1,039,198	982,877	899,991	774,688
$\dot{W}_{tot}$ (Btu/hr)	1,274,090 (max)	1,429,510	1,493,590	1,514,390	1,498,220	1,361,940

Table 16 Double Flash System for $_5Q_6$ = 863,400 Btu/hr

$P_9 = 200$ psia
$T_9 = 280$ °F
$\dot{m}_9 = 292000$ lbm/hr

$T_5 = 915$ °F
$P_{27} = 8$ psia

P_{10} (psia)	45	40	35	30	25	20
X_{10}	0.00614	0.01396	0.02252	0.03199	0.04268	0.05510
$\dot{m}_{16}$ (lbm/hr)	1792.88	4076.32	6575.84	9341.08	12463	16089
h_{16} (Btu/lbm)	1172.0	1169.7	1167.1	1164.1	1160.6	1156.3
h_{17} (Btu/lbm)	1489.0	1434.5	1331.2	1279.6	1247.2	1223.4
S_{17} (Btu/lbm-°R)	1.9773	1.9491	1.8746	1.8399	1.8244	1.8208
T_{17} (°F)	915	806.4	595.3	487.2	418.1	366.6
P_{18} (psia)	20.26	18.92	17.52	16.09	14.54	12.88
h_{18} (Btu/lbm)	1378.2	1338.5	1257.1	1219.5	1198.4	1185.6
${}_{17}\dot{W}_{18}$ (Btu/hr)	198,651	391,327	487,270	561,399	608,194	608,164
X_{14}	0.04848	0.04452	0.04028	0.03527	0.02977	0.02331
$\dot{m}_{20}$ (lbm/hr)	15862	16894	18073	19310	20785	22520
h_{20} (Btu/lbm)	1181.6	1196.4	1191.3	1184.7	1179.1	1174.9
S_{20} (Btu/lbm-°R)	1.7660	1.7931	1.7948	1.7954	1.7999	1.8062
h_{27} (Btu/lbm)	1113.8	1131.2	1132.3	1132.7	1135.5	1139.3
${}_{20}\dot{W}_{27}$ (Btu/hr)	1,075,444	1,101,489	1,066,307	1,004,120	906,226	801,712
$\dot{W}_{tot}$ (Btu/hr)	1,274,090 max	1,492,820	1,553,580	1,565,520	1,514,420	1,409,880

Table 17 Double Flash System for ${}_5Q_6$ = 1,0709,250 Btu/hr

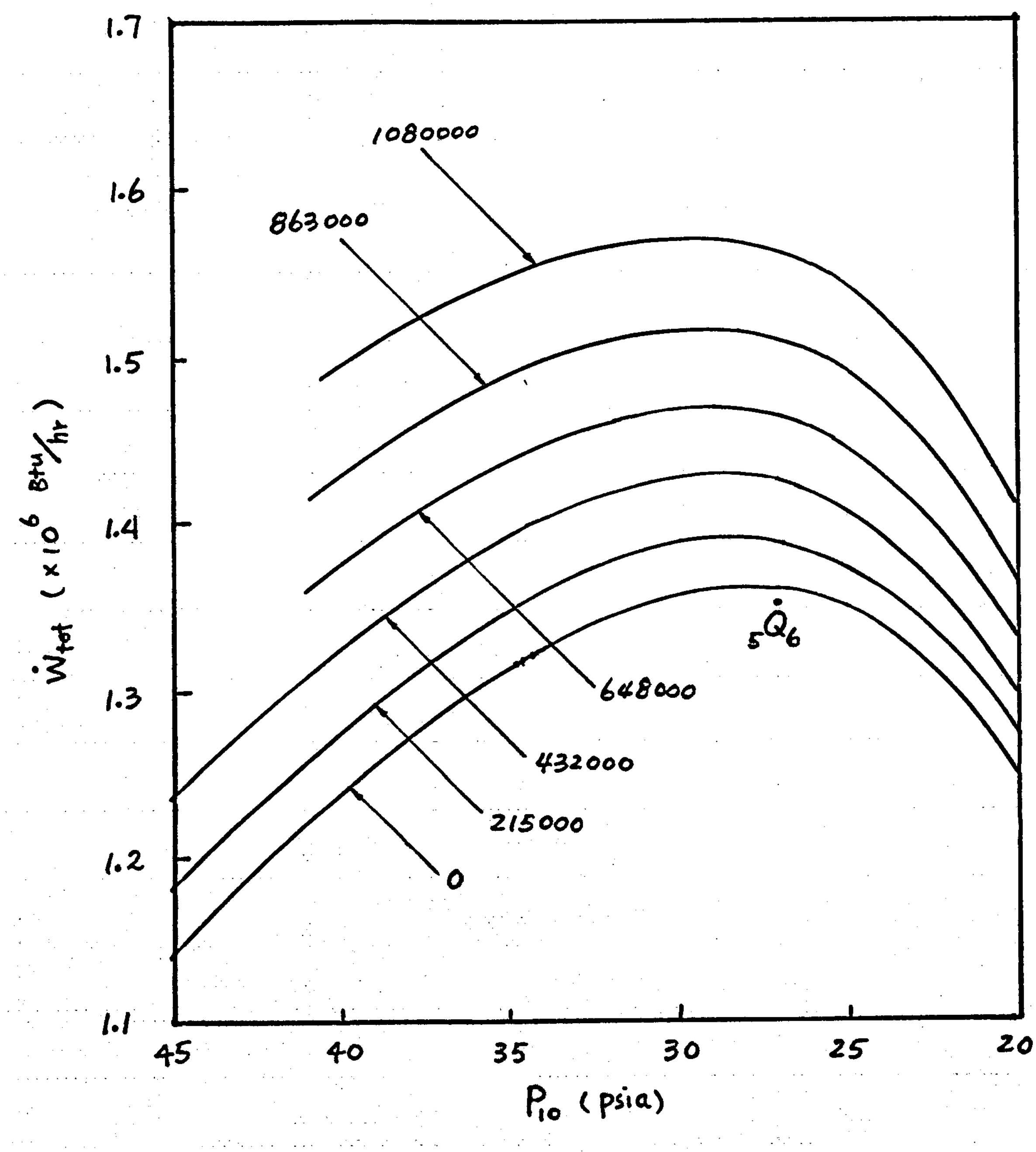


Fig. 15 Double Flash System - $\dot{W}_{tot}$ v.s. P_{10}

choice of low pressure flash tank condition in our tables is based on Equ. (13).

As the amount of superheating $_5Q_6$ is increased, the maximum total turbine output is also increased. This is shown in Table 18 as well as Fig. 16. The maximum amount of $_5Q_6$ that can be transferred to the steam superheater is dependent on the temperature of exhaust gas. In our computation, the highest temperature of T_5 is set at 915°F.

The effect of superheating $_5Q_6$ to the total power output is further explained in Table 19. In which W_{tot} is defined as

$$W_{tot} = W_{tot} - (W_{tot})_o \qquad (16)$$

$(W_{tot})_o$ represents the total turbine power output of the system when $_5Q_6 = 0$. W_{tot} is the power output increase due to superheating. The percent of power output increase $W_{tot} \times 100$ v.s. the amount of superheating $_5Q_6$ is plotted in Fig. 17. The ratio of total power output increase to $_5Q_6$ is plotted in Fig. 18.

$P_9 = 200$ psia
$T_9 = 280°F$
$\dot{m}_9 = 292000 \ \frac{lbm}{hr}$

$P_{10} = 30$ psia
$P_{14} = 16.1$ psia
$T_{14} = 217°F$

$P_{27} = 8$ psia

${}_5\dot{Q}_6$ ($\frac{Btu}{hr}$)	T_{17} (°F)	X_{18} or T_{18}	${}_{17}\dot{W}_{18}$ (kw)	X_{27} or T_{27}	${}_{20}\dot{W}_{27}$ (kw)	$\dot{W}_{tot}$ (kw)
0	250	0.965	126	0.963	273	399
216,000	296	0.987	130	0.963	276	406
432,000	343	232°	138	0.967	279	417
648,000	382	266°	146	0.974	282	428
863,000	439	315°	156	0.985	288	444
1,079,000	487	357°	164	0.993	294	458

Table 18 Double Flash System - The Relation Between Superheating and Power Output at Optimal Flashing Condition

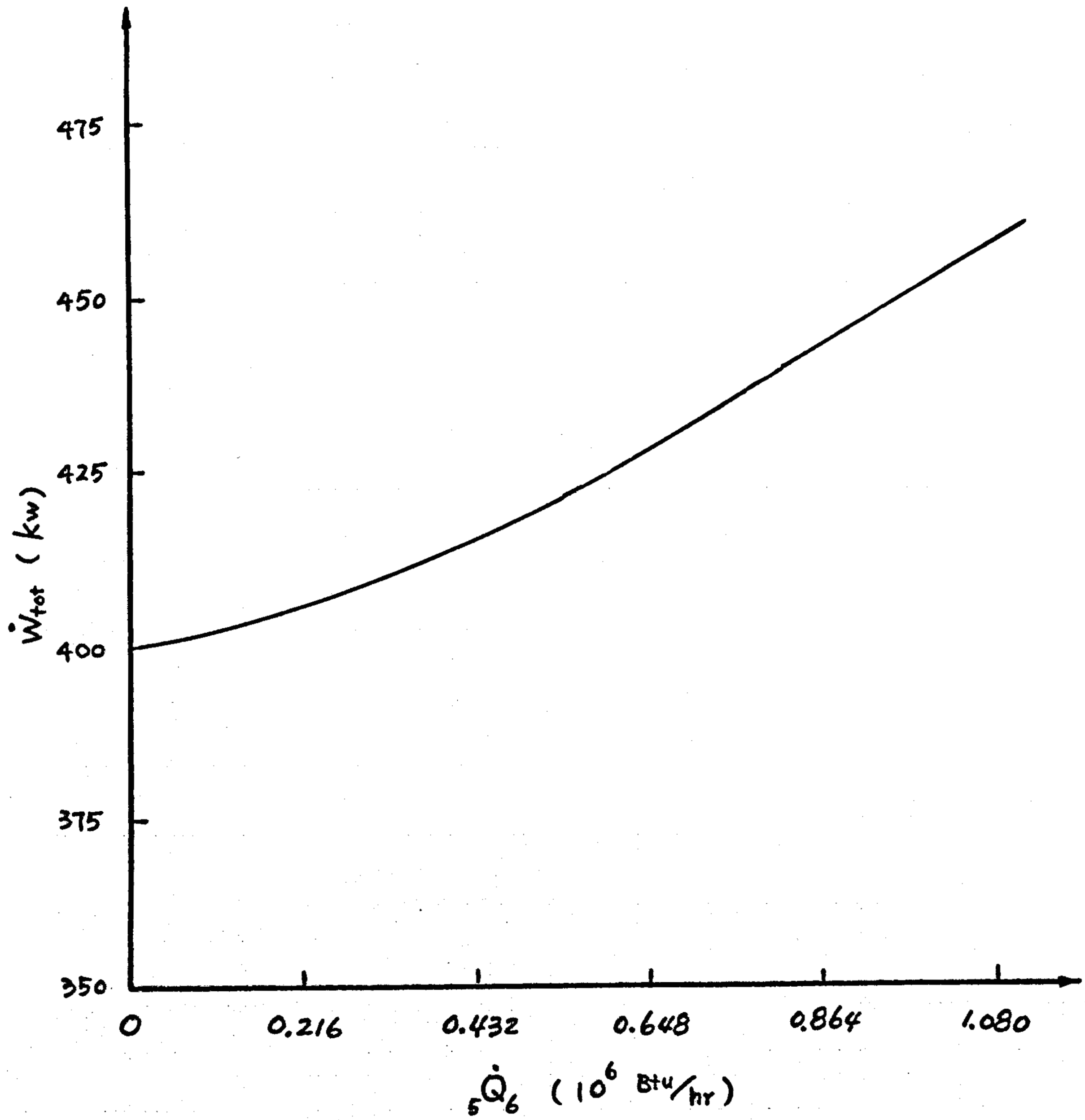


Fig. 16 Double Flash System - $\dot{W}_{tot}$ v.s. ${}_5\dot{Q}_6$ at Optimal Flashing Condition

$$\Delta \dot{W}_{tot} = \dot{W}_{tot} - (\dot{W}_{tot})_{\dot{Q}=0}$$

${}_5\dot{Q}_6$ $(\frac{Btu}{hr})$	$\Delta \dot{W}_{tot}$ $(\frac{Btu}{hr})$	$\frac{\Delta \dot{W}_{tot}}{(\dot{W}_{tot})_{\dot{Q}=0}} \times 100$	$\frac{\Delta \dot{W}_{tot}}{{}_5\dot{Q}_6}$
0	0	0	/
215,850	26929	1.98	0.1248
431,700	63773	4.69	0.1477
647,550	99645	7.33	0.1539
863,400	154451	11.36	0.1789
1,079,250	205584	15.12	0.1905

Table 19 Double Flash System - Superheating and Power Output at Optimal Flashing Condition

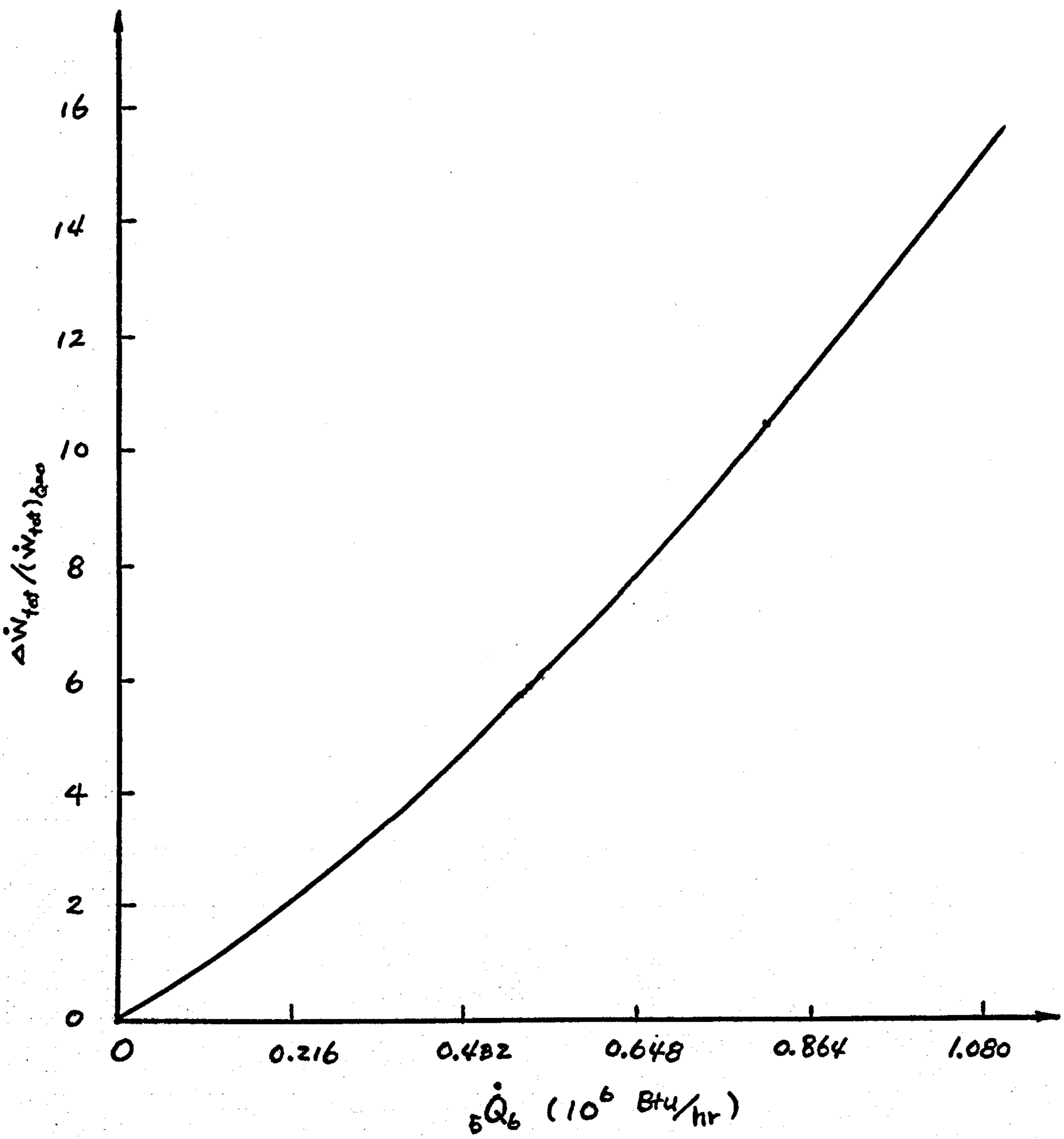


Fig. 17 Double Flash System - $W_{tot}/(W_{tot})$ Q = 0 v.s. $_5Q_6$ at Optimal Flashing Condition

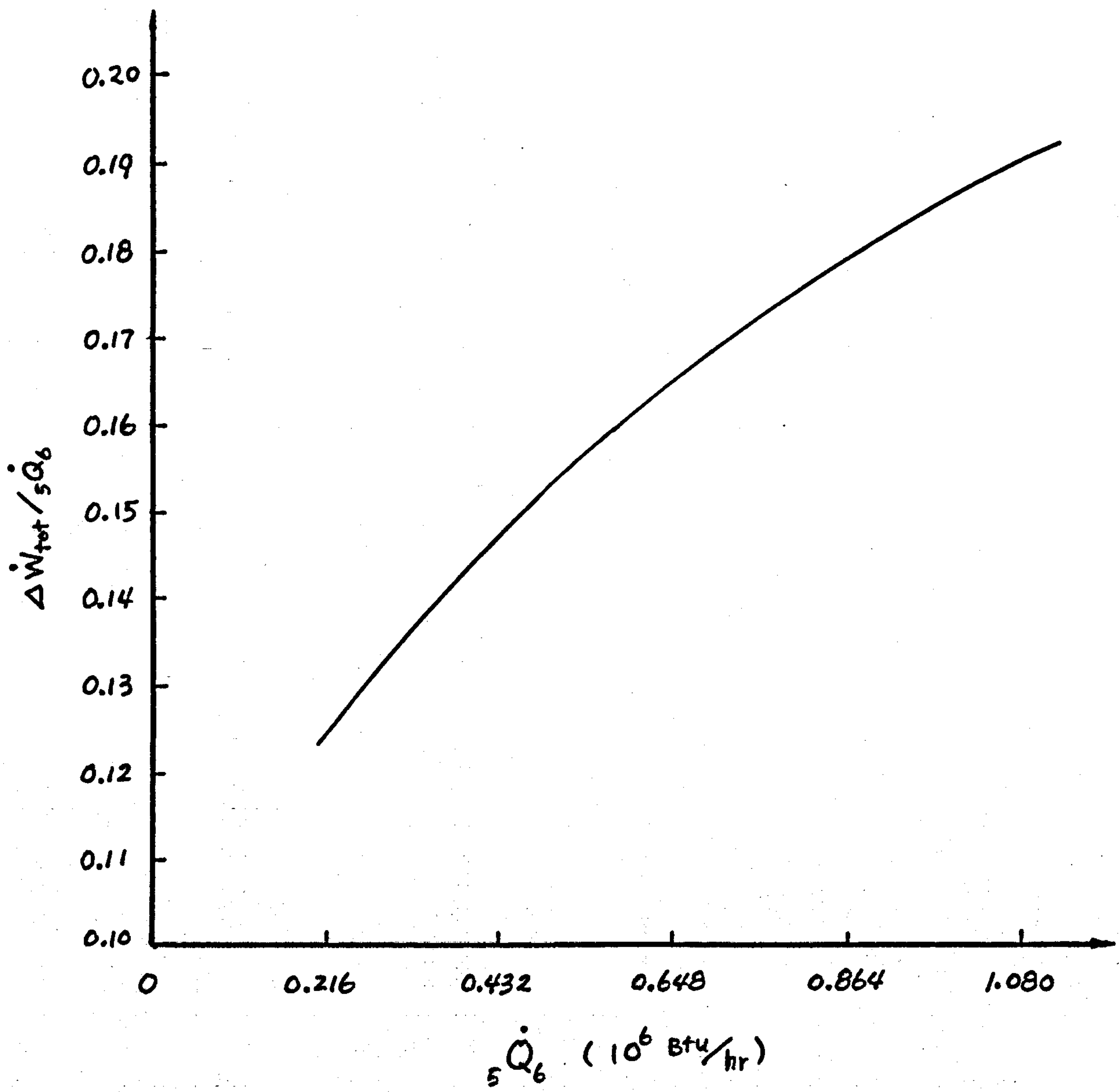


Fig. 18 Double Flash System - $W_{tot}/{}_5Q_6$ at Optimal Flashing Condition

Chapter 6

Comparison of Single-Flash System and Double Flash System

The double flash system is more efficient thermodynamically than the single flash system. This results primarily from the following two reasons. In the single flash system, the flash tank pressure is lower than the pressure in the high pressure flash tank of a corresponding double flash system. Therefore, some of the steam expansion in the single flash tank would be utilized by the high pressure steam turbine of a corresponding double flash system. Secondly, in the double flash system, a smaller amount of steam flows through the steam superheater, and therefore reaches a higher temperature than the single flash system. From the second law of thermodynamics, the higher the average temperature at which the heat is transferred to the cycle, the higher the thermal efficiency of the system.

Table 20 is constructed from the computations in chapter 4 and chapter 5. We are able to make comparison for the same set of flow conditions at the inlet and and exit of the systems. Note that for the same amount of steam superheating from the exhaust gas, the power output of the double flash system is 30% more than the power output of the corresponding single flash system. This result is more or less independent of the amount of superheating involved. In Fig. 19, the power output of the single flash system and the double flash system are compared with respect to the amount of steam superheating involved. This figure is derived from Table 20.

If double flash systems with steam superheating are compared

$$\Delta\dot{W} = \dot{W}_{Double} - \dot{W}_{single}$$

${}_5\dot{Q}_6$ ($\frac{Btu}{hr}$)	$\dot{W}_{single}$ (kw)	$\dot{W}_{Double}$ (kw)	$\Delta\dot{W}$ (kw)	$\frac{\Delta\dot{W}}{\dot{W}_{single}} \times 100$
0	304	399	95	31.1
215,850	309	406	97	31.4
431,700	316	417	101	31.9
647,550	326	428	102	31.1
863,400	338	444	106	31.5
1,079,250	350	458	108	30.9

Table 20 Comparison of Power Outputs of Double Flash System to Single Flash System

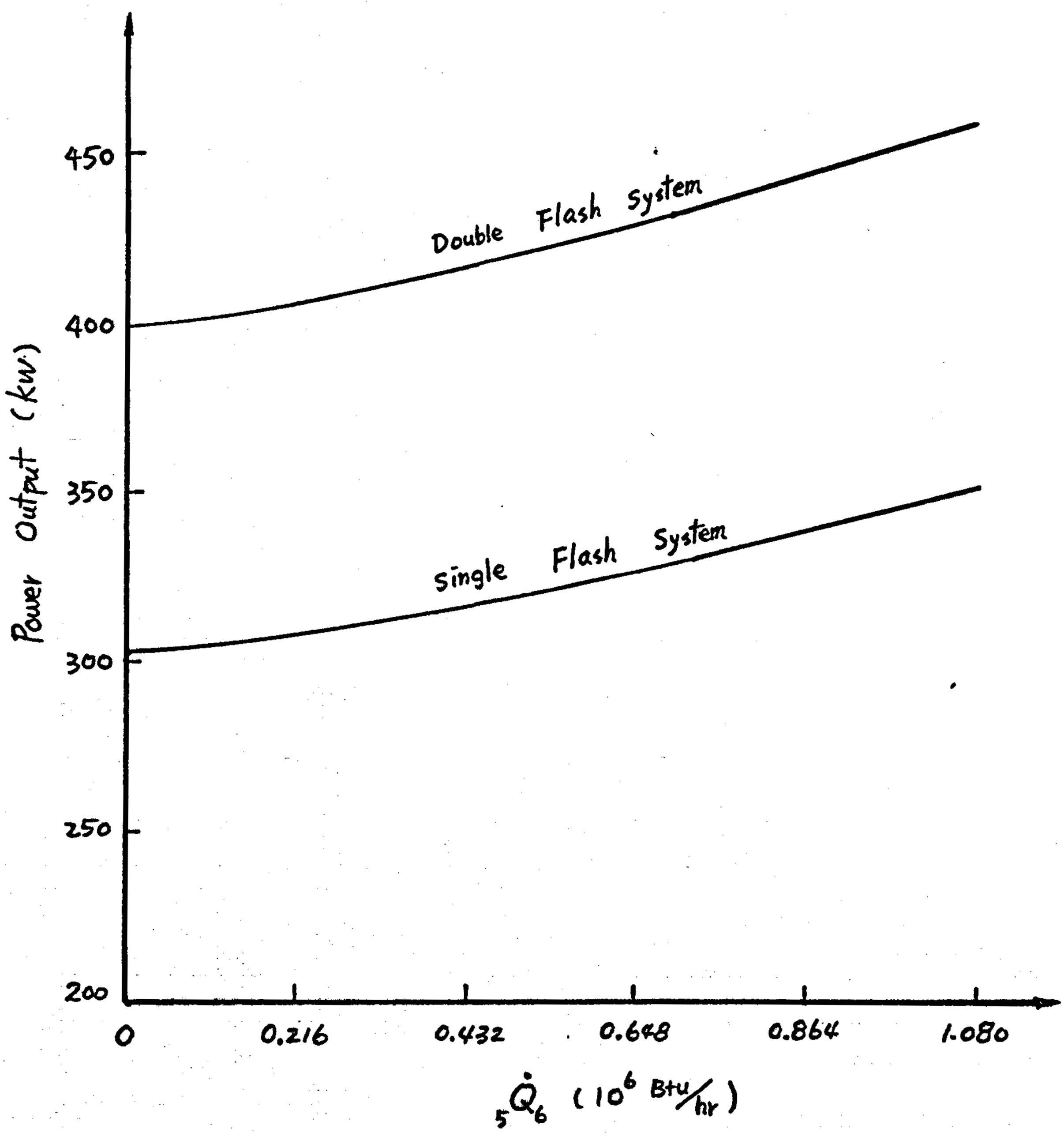


Fig. 19 Comparison of Double Flash System to Single Flash System-Power Output v.s. Exhaust Heat Input

with single flash systems without steam superheating from exhaust gas, we are able to see a big improvement. Of course, the improvement in power output is dependent on the amount of superheating involved. This is shown in Table 21. Fig. 20 is derived from Table 21, in which the percent power output increase is plotted against steam superheating ${}_5Q_6$.

$$({}_{17}\dot{W}_{18})_{\dot{Q}=0} = 1{,}037{,}740 \ \text{Btu/hr}$$

$$\Delta \dot{W} = \dot{W}_{tot} - ({}_{17}\dot{W}_{18})_{\dot{Q}=0}$$

${}_5\dot{Q}_6$ (Btu/hr)	$\Delta\dot{W}$ (Btu/hr)	$\frac{\Delta\dot{W}}{({}_{17}\dot{W}_{18})_{\dot{Q}=0}} \times 100$
0	322,194	31.05
215,850	349,123	33.64
431,700	385,967	37.19
647,550	421,839	40.65
863,400	476,645	45.93
1,079,250	527,779	50.86

Table 21 Comparison of Power Outputs of Double Flash System to Single Flash System Without Superheating

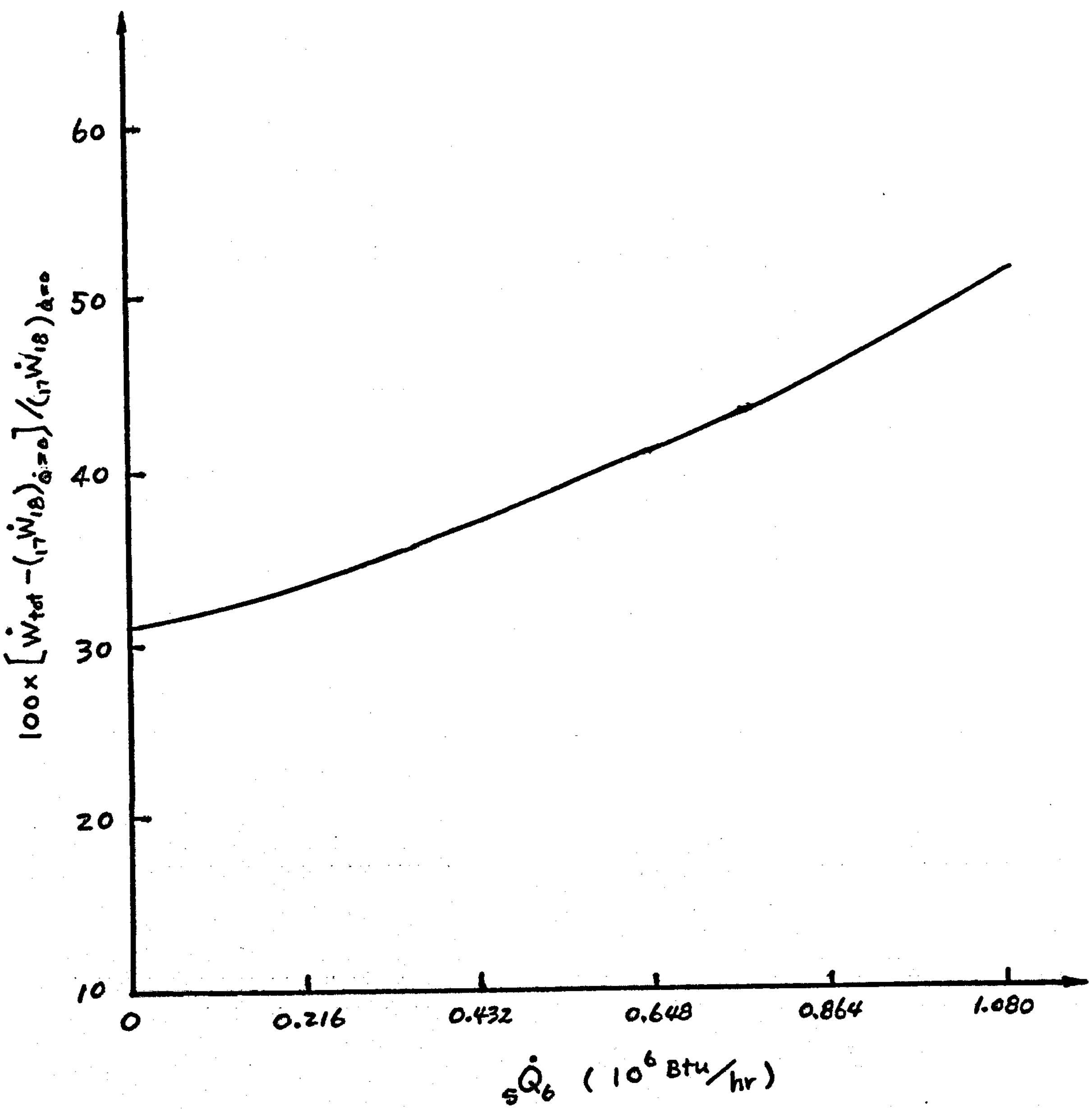


Fig. 20 Comparison of Double Flash System with Superheating to Single Flash System Without Superheating

Chapter 7

Binary System

To take advantage of the relative large temperature difference of the two heat sources (brine and exhaust gas), a binary system may be considered. A schematic diagram of one design of a binary system is shown in Fig. 21. There are two turbines and a number of heat exchangers in the system. The performance of the binary system depends a great deal on the design and operation conditions of these heat exchangers and turbines. It also depends significantly on the selection of working fluids in the two cycles. In the lower cycle, if it is to maximize the recovery of brine heat, heat exchanger A in the figure should be used as an evaporator and heat exchanger B should be used as a superheater. On the other hand, if it is to maximize the recovery of exhaust heat from the gas engine, heat exchanger A should be used as preheater and heat exchanger B should be used as an evaporator and superheater. In the higher cycle, heat exchanger C should be used as a preheater or can be omitted, heat exchanger D should be used as an evaporaator and superheater.

Since the thermodynamic analysis of a binary cycle involves so much of the operational characteristics of heat exchangers and turbines, we need to make some assumptions about their operations in order to simplify the analysis. The objective of our analysis is only to show that the binary cycle is a promising alternative to the single flash or double flash system. Our results of analysis should not be used directly for design purposes.

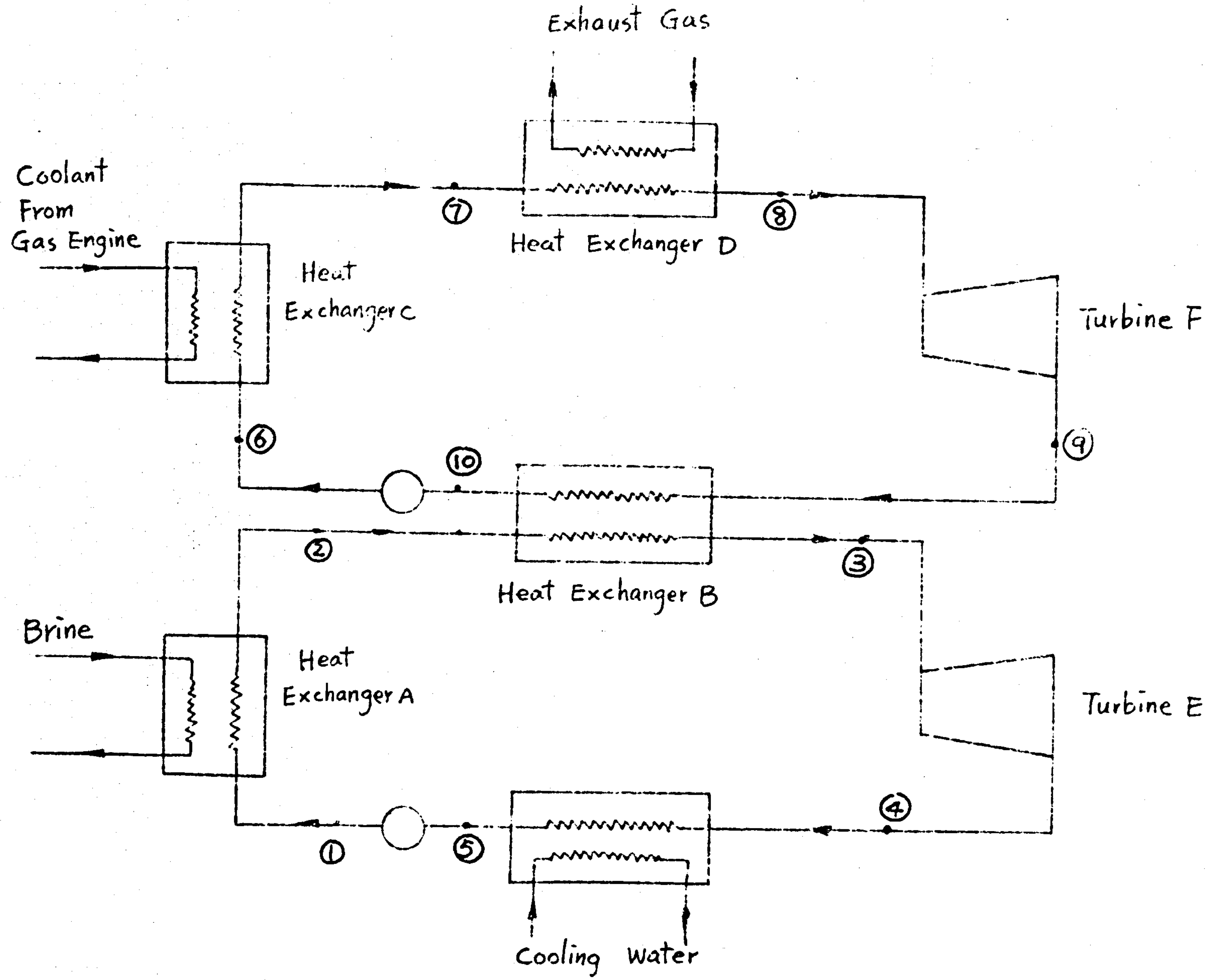


Fig. 21 Shematic Diagram of a Binary System

The following assumptions are made in our sample computations. Steam at different pressures are used for both cycles. To maximize the brine heat recovery, as mention earlier, heat exchanger A is considered as an evaporator, heat exchanger B is considered as a superheater for lower cycle and a condenser for higher cycle. Heat exchanger C is omitted, heat exchanger D is considered as an evaporator and superheater. For the two steam turbines, the minimum quality requirement is arbitarily assumed to be 95%. At the inlet of the condenser in the lower cycle, pressure p_4 is fixed at 8 psia, and the quality X_4 is fixed at 95%. At the exit, pressure P_5 is fixed at 8 psia, and the quality X_5 is fixed at 0. In the higher cycle, at the exit of heat exchanger D, we arbitarily set the pressure P_8 = 800 psia, and temperature T_8 = 860°F, this temperature can be compared with temperature 915°F of exhaust gas. At heat exchanger B, we are arbitarily required T_3 to be 5°F higher than T_{10}. At heat exchanger A, different pressures are used in order to obtain different temperature at section 2. Of course, the temperature at section 2 should be less than the brine temperature of 280°F.

For a given pressure at heat exchanger A, the power output per unit mass flow rate at turbine E can be computed as ${}_3W_4$. We can also compute the power output per unit mass flow rate of the lower cycle at turbine F as ${}_8W_9$. The sum of both outputs is the total output of the binary cycle. As observed in the flash system, the power needed for pumps is neglected. If the mass flow rate in the lower cycle can be evaluated from the performance characteristics of heat exchanger A, the total power output of the system is obtained. Some of the equations used in our computations are listed in the following.

$_1q_2 = h_2 - h_1$

$_2q_3 = {}_{10}Q_9 = h_3 - h_2$

$M_9/M_2 = (h_3 - h_2)/(h_q - h_{10})$

$$_7Q_8 = \left(\frac{M_9}{M_z}\right)(h_8 - h_9)$$

$_3W_4 = h_3 - h_4$

$$_8W_9 = \left(\frac{m_9}{m_z}\right)(h_8 - h_9)$$

$W_{tot} = {}_3W_4 + {}_8W_9$

The results of computation are included in Table 22. From this table, we noted that the total power output decreases as lower cycle evaporator pressure decreases. This is reasonable because the evaporation temperature is decreased. For evaporator pressure less than 21 psia, no higher cycle is needed, because the quality of steam at turbine G is going to be greater than 95%.

If we want to maximize the recovery of exhaust heat from gas engine, different computations are required. These computations are not included in this report.

P_2 (psia)	T_2 (°F)	T_3 (°F)	${}_1\dot{Q}_2$ ($\frac{Btu}{lbm}$)	$\dot{m}_9/\dot{m}_2$	${}_7\dot{Q}_8$ ($\frac{Btu}{lbm}$)	${}_8\dot{W}_9$ ($\frac{Btu}{lbm}$)	${}_3\dot{W}_4$ ($\frac{Btu}{lbm}$)	$\dot{W}_{tot}$ ($\frac{Btu}{lbm}$)
45	274	369	1021	0.053	57	9	130	139
40	267	346	1019	0.044	49	9	120	129
35	259	320	1016	0.034	39	8	108	116
30	250	293	1013	0.024	28	6	96	102
25	240	261	1010	0.012	14	4	81	85
21	231	231	1006	0	/	/	67	67

Table 22 Summary of a Sample Binary System