CONDENSERS FOR TURBINE GENERATORS: THE ALTERNATIVES

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ABSTRACT

This paper presents a method of evaluating turbine generator condensing systems for small power plants. The four condensing systems evaluated are: once-through condensers, evaporative condensers, conventional cooling tower-condensing systems and air cooled condensers. The evaluation is made on a present value basis to reflect the cost of installing and operating the alternative systems over a 20-year period. The method indicates a specific order of preference for the type of system desirable for the location evaluated based on site specific factors such as ambient wet- and dry-bulb temperatures throughout the year; water availability, quality and cost; water disposal costs; and site limitations.

INTRODUCTION

Spread sheets can be used for evaluating various systems for condensing steam from a turbine generator as they might be used in a waste-to-energy plant. While the primary function of a waste-to-energy facility is to reliably incinerate refuse, the designer also has the responsibility to optimize the design of the heat recovery equipment that is installed. The type of condensing system and the design condenser vacuum pressure to be used must therefore be addressed. The types of condensing systems to be considered in the development of these spread sheets are:

(a) Once-Through Condenser.
(b) Evaporative Condenser.
(c) Conventional Cooling Tower-Condenser System.
(d) Air Cooled Condenser.

This paper does not consider two other possibilities, the water-assisted air cooled condenser and the wet/dry cooling tower. These address the specific problems of the cost or availability of water and the environmental concerns regarding a plume. The methodology discussed in this paper is applicable to evaluating these alternatives.

BASIS OF SYSTEMS EVALUATION

The basis of this study is a 1200 ton/day (1100 t/day) waste-to-energy plant firing refuse with a higher heating value of 4500 Btu/lb (10,000 kJ/kg). The selection of boiler types, the steam conditions, and the type of steam cycle are outside the scope of this paper. The starting point of this study is a steam flow to the condenser of approximately 232,000 lb/hr (105,000 kg/hr) with an enthalpy of 990 Btu/lb (2300 kJ/kg) at a vacuum of 2.5 in. Hg (8 kPa) absolute. The temperature data used in the evaluation of condensing systems is normally readily available as load duration

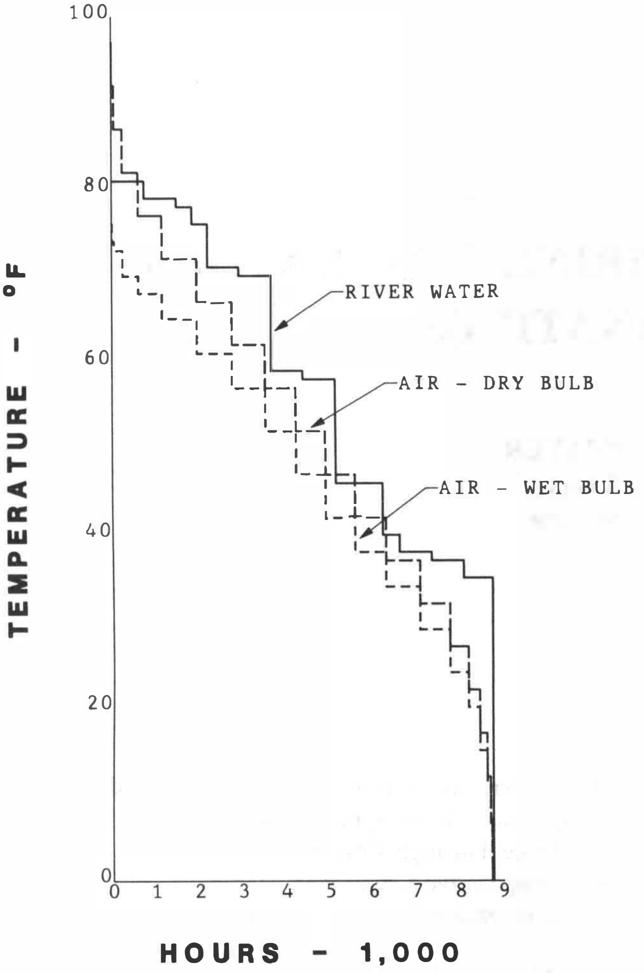

FIG. 1 COOLANT TEMPERATURES

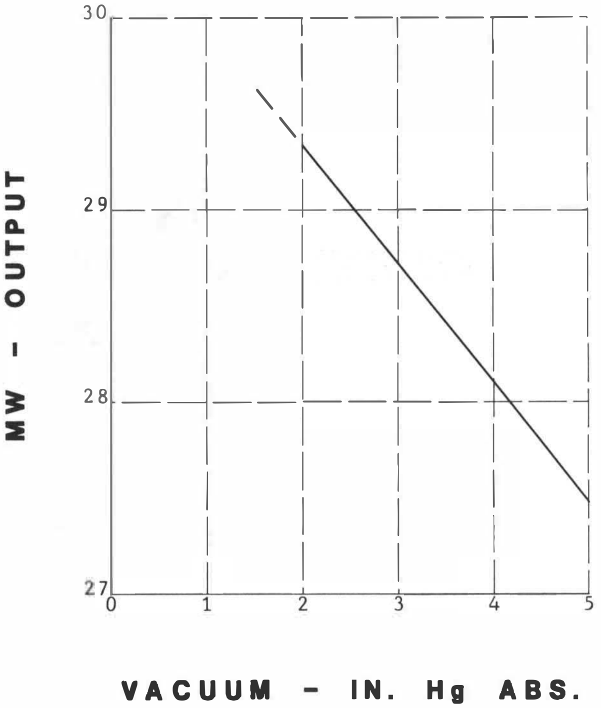

FIG. 2 POWER OUTPUT vs CONDENSER VACUUM

data for wet- and dry-bulb temperatures [1] and river water temperatures [2]. These were used for a typical installation and are presented in Fig. 1 in a load-duration format. The 1% dry-bulb temperature for the location studied is 91°F (306K); the 1% wet-bulb temperature, 78°F (299K). While condensing systems are frequently designed on the basis of these temperatures for the specific site, they are not the conditions that the facility will actually experience. Therefore, in order to assess the impact of the decision of the design values to be used, the annual operating costs must be determined.

Some of the data and assumptions used in this study are as follows:

(a) The steam cycle, number of feedwater heaters, steam conditions, etc. have been determined and heat balances and turbine generator power outputs for 2, 3, 4, and 5 in. Hg (7, 10, 14, and 17 kPa) absolute vacuum were calculated. The power output of the turbine generator at various turbine outlet conditions is shown in Fig. 2.

(b) A 7°F (4°C) approach temperature is used for all heat exchange equipment.

(c) The pressure drop from the turbine generator exhaust flange to the evaporative condenser or air cooled condenser is 0.1 in. Hg (0.3 kPa).

(d) The minimum attainable vacuum for a turbine with a condenser placed directly under the turbine is 1.5 in. Hg (5 kPa) absolute at the turbine.

(e) The minimum attainable vacuum for a turbine with an evaporative or an air cooled condenser is 2.0 in. Hg (7 kPa) at the turbine.

(f) Two-speed fans are used in evaporative condensers and conventional cooling towers to minimize power consumption.

(g) The cycles of concentration used in the evaporative condenser water system is 7; in the cooling tower condenser system, 6.

(h) The average value of the net power generated is $36.75 per mWh.

(i) The cost of makeup water is $0.75/1000 gal ($0.75)/3800 L).

(j) The cost of chemical treatment of the water for the evaporative condenser or cooling tower is $0.918/1000 gal ($0.918/3800 L) of blowdown.

(k) The cost of once-through cooling water (non-consumptive use) is $0.0006/1000 gal ($0.0006/3800 L).

(l) The cost of waste water disposal to the local sewage plant is $1.43/1000 gal ($1.43/3800 L).

*(m)*The value of money used in all present value calculations is 10%.

(n) Maintenance costs were not included in the evaluation.

(o) Plant availability is 85%.

Many of the above assumptions are site specific and must be adjusted for the actual facility under consideration. However, the use of spread sheet calculations makes changes to the assumptions and recalculation of the results fast and simple. Also, assumptions such as the approach temperature should be tested. However, using different approach temperatures involves considerable equipment sizing, cost estimating and evaluation. This was not done for the purposes of this paper. However, it must be done to optimize the total cost of the installation after a specific type of condenser system has been selected.

DESCRIPTION OF EQUIPMENT

The once-through condensing systems are based on a conventional surface condenser placed directly below the turbine generator. Cooling water is drawn in a conventional intake, consisting of trash racks, traveling screens and three, one-half capacity circulating pumps. The cooling water is discharged downstream from the intake.

The evaporative condenser systems are based on a large number of stainless steel tube sections configured in an overhead structure with two-speed cooling fans and a spray water recirculation system, a concrete spray water collection basin, and three, one-half capacity, water circulating pumps.

The cooling tower-condensing systems include a conventional surface condenser placed directly below the turbine generator, cooling water circulating piping, a ceramic cooling tower using two-speed fans and three, one-half capacity, circulating pumps.

The air cooled condensers are constructed with large finned tube bundles, arranged in an A-frame configuration in multiple modules. Because of the large surface area requirements, many modules, each equipped with fans, are required.

The estimates for each of the foregoing alternates include all foundation and installation costs so that a relative capital cost estimate can be made. These costs appear in the tables discussed below.

EVALUATION

The evaluations were all calculated on a personal computer, using a spreadsheet program. Equations were built into the program where possible to eliminate repetitive calculations.

The initial evaluation task is to determine the net power generation resulting from a specific equipment selection. Since instantaneous power generation is dependent on the temperature of the coolant, and this varies with time, spread sheets similar to the one shown in Fig. 3 were prepared for each alternative. These spread sheets take into account the coolant temperature and the fan and pump power consumption to develop an annual power generation. In each case, the effect of the coolant temperature on the condenser vacuum and the vacuum on turbine power output is evaluated by using performance data supplied by equipment suppliers or by calculation. The annual power generation data for each alternate design vacuum is then assembled on the summary sheet for each specific condensing system. On all of these sheets each alternate is identified by the design pressure that will be achieved at the 1% dry-bulb or wet-bulb air temperature. These are then assembled on a summary sheet for the specific system as shown in Figs. 4–7. The summary evaluation determines the present value of the capital costs and the value of 20 years of power generation. The cost of water consumption, sewer disposal of blowdown and chemicals are neglected at this point because they do not affect the selection of the optimum vacuum. These calculations account only for the power output of the turbine generator minus those electric drives (pumps, fans, etc.) related to the condensing equipment. Power consuming equipment in the balance of the plant that is not related to the condensing system are neglected. The optimum selection for each type of condensing system is then compared on the final summary sheet shown in Fig. 8. This final summary clearly indicates the order of preference for the various types of condensing systems considered:

(a) Once-Through Condenser.

(b) Evaporative Condenser.

FIG. 3 SAMPLE SPREAD SHEET
(Evaporative Condenser 3 in Hg Design)

TEMP RANGE DEG F	HOUR	MCWB DEG F	COND VACUUM IN HG	TG POWER MW	FAN PWR MW	PUMP POWER MW	OUT MW	ANNUAL OUTPUT MWH
95/99	4	76	2.95	29.158	0.183	0.100	28.875	115.501
90/94	47	74	2.88	29.202	0.183	0.100	28.919	1,359.199
85/89	190	73	2.80	29.252	0.183	0.100	28.969	5,504.148
80/84	366	70	2.60	29.377	0.183	0.100	29.094	10,648.550
75/79	564	68	2.50	29.440	0.183	0.100	29.157	16,444.548
70/74	806	65	2.40	29.503	0.183	0.100	29.220	23,550.998
65/68	808	61	2.25	29.597	0.183	0.100	29.314	23,685.308
60/64	761	57	2.05	29.722	0.183	0.100	29.439	22,402.851
55/59	701	52	2.00	29.753	0.183	0.100	29.470	20,658.470
50/54	676	47	2.00	29.753	0.183	0.100	29.470	19,921.720
45/49	674	42	2.00	29.753	0.103	0.100	29.550	19,916.700
40/44	713	38	2.00	29.753	0.103	0.100	29.550	21,069.150
35/39	784	34	2.00	29.753	0.103	0.100	29.550	23,167.200
30/34	697	29	2.00	29.753	0.103	0.000	29.650	20,666.050
25/29	426	24	2.00	29.753	0.103	0.000	29.650	12,630.900
20/24	260	20	2.00	29.753	0.103	0.000	29.650	7,709.000
15/19	165	15	2.00	29.753	0.103	0.000	29.650	4,892.250
10/14	73	11	2.00	29.753	0.103	0.000	29.650	2,164.450
5/9	30	6	2.00	29.753	0.103	0.000	29.650	889.500
0/4	5	2	2.00	29.753	0.103	0.000	29.650	148.250
-5/-1	0	-4	2.00	29.753	0.103	0.000	29.650	0.000
TOTAL POWER OUTPUT								257,544.743
POWER OUTPUT — (85% AVAILABILITY)								218,913.031

FIG. 4 COMPARISON OF ONCE-THROUGH CONDENSERS

ALTERNATE	ALT NO. 1	ALT NO. 2	ALT NO. 3
Design Vacuum — in. Hg	3	2.5	2
Capital cost	$1,413,000	$1,651,000	$2,130,000
Generation — Net mWh/yr	219,397.457	218,010.801	216,261.944
Value — $/yr	$8,056,274.62	$8,005,356.61	$7,941,138.58
PV 20 Yrs Generation — $	$68,591,122.12	$68,157,606.20	$67,610,853.90
PV Construction Cost — $	($1,226,484.00)	($1,433,068.00)	($1,848,840.00)
Net Present Value — $	$67,364,638.12	$66,724,538.20	$65,762,013.90

FIG. 5 COMPARISON OF EVAPORATIVE CONDENSERS

ALTERNATE	ALT NO. 1	ALT NO. 2	ALT NO. 3	ALT NO. 4
Design Vacuum — in. Hg	5	3	2.5	2
Capital cost	$1,075,000.00	$1,383,600.00	$1,641,000.00	$2,029,000.00
Net Power Generation — mWh/yr	218,256.607	218,913.031	218,909.112	219,065.880
Value of Power — $/yr	$7,867,502.61	$8,038,486.50	$8,038,342.59	$8,044,099.11
PV 20 Yrs Generation — $	$66,983,917.21	$68,439,674.05	$68,438,448.83	$68,487,459.85
PV Construction Cost — $	($933,100.00)	($1,200,964.80)	($1,424,388.00)	($1,761,172.00)
Net Present Value — $	$66,050,817.21	$67,238,709.25	$67,014,060.83	$66,726,287.85

FIG. 6 COMPARISON OF COOLING TOWER—CONDENSER SYSTEMS

ALTERNATE	ALT NO. 1	ALT NO. 2	ALT NO. 3
Design Vacuum — in. Hg	3	2.5	2
Capital Cost	$1,693,400.00	$1,819,900	$2,322,800.00
Generation — Net mWh/yr	217,873.490	217,964.180	216,616.950
Value — $/yr	$8,000,314.55	$8,003,644.69	$7,954,174.40
PV 20 Yrs Generation — $	$68,114,678.10	$68,143,030.89	$67,721,840.88
PV Construction Cost — $	($1,469,871.20)	($1,579,673.20)	($2,016,190.40)
Net Present Value —$	$66,644,806.90	$66,563,357.69	$65,705,650.48

(c) Conventional Cooling Tower-Condenser System.

(d) Air Cooled Condenser.

DISCUSSION OF RESULTS

The once-through condenser benefits from generating slightly more power than the evaporative condenser and avoidance of the fairly significant water, sewerage and chemical costs. However, as noted on the following pages, permitting issues may preclude the use of once-through condensing.

The evaporative condenser benefits from the greater power generation which results from this type of unit's ability to achieve a lower absolute vacuum pressure more closely corresponding to the wet-bulb temperature. Also, since the circulating water temperatures in the evaporative cooled system will be lower, the cycles of concentration will be slightly greater and the blowdown will be less for the evaporative condenser. Therefore, the evaporative condenser's lower water and sewer costs and higher power output makes this alternative more attractive. The air cooled condenser suffers from higher capital cost, and the greater power

FIG. 7 COMPARISON OF AIR COOLED CONDENSER ALTERNATES

ALTERNATE	**ALT NO. 1**	**ALT NO. 2**	**ALT NO. 3**
Design Vacuum — in. Hg	**5**	**3**	**2.5**
Capital Cost	**$3,691,000**	**$6,173,000**	**$8,101,500**
Generation — Net mWh/yr	**212,600.378**	**209,776.699**	**206,019.895**
Value — $/yr	**$7,806,685.88**	**$7,703,000.39**	**$7,565,050.54**
PV 20 Yrs Generation — $	**$66,466,123.58**	**$65,583,345.30**	**$64,408,840.34**
PV Construction Cost — $	**($3,203,788.00)**	**($5,358,164.00)**	**($7,032,102.00)**
Net Present value — $	**$63,262,335.58**	**$60,225,181.30**	**$57,376,738.34**

FIG. 8 FINAL SUMMARY SHEET

Type	**Once Through Condenser**	**Evaporative Condenser**	**Conventional Cooling Tower — Condenser**	**Air Cooled Condenser**
Optimum Design Vacuum — in. Hg	3	3	3	5
Capital Cost	($1,413,000.00)	($1,383,600.00)	($1,693,400.00)	($3,691,000.00)
Net Power Generation — mWh/yr	219,397.457	218,913.031	217,873.490	212,600.378
Value of Power — $/yr	$8,056,274.62	$8,038,486.50	$8,000,314.55	$7,806,685.88
Annual Water Usage 1000 gal/yr	9,719,900	222,040	228,300	0
Cost of Water — S/yr	($5,831.94)	($166,530.00)	($171,225.00)	$0.00
Cost of Chemicals — $/yr	$0.00	($29,118.96)	($58,237.92)	$0.00
Annual Blowdown to Sewer — 1000 gal/yr	0	31,720	63,440	0
Sewer Cost — $/yr	$0.00	($45,359.60)	($90,719.20)	$0.00
PV Capital Cost — $	($1,226,484.00)	($1,200,964.80)	($1,469,871.20)	($3,203,788.00)
PV 20 yrs Power Generation — $	$68,591,122.12	$68,439,674.05	$68,114,678.10	$66,466,123.58
PV 20 yrs Water, Chemical & Sewer use — $	($49,653.14)	($2,051,946.88)	($2,726,030.57)	$0.00
Net Present Value — $	$67,314,984.99	$65,186,762.37	$63,918,776.33	$63,262,335.58

requirements for cooling fans. The fan power requirements are greater than the power requirements for the pumps and fans in a conventional cooling tower condensing system. As shown in Fig. 8, the costs associated with cooling tower makeup, blowdown and chemicals is significant but not enough to affect the selection of the condensing system in favor of an air-cooled condenser. These financial considerations still leave a lot of unanswered questions that may affect the final selection. Some of the questions that must be addressed are these:

(a) While a once-through system might be preferable, a lengthy regulatory delay could result in cost escalations that would offset any potential saving.

(b) Equipment selection may be affected by such costs as: water, blowdown disposal and chemicals for treating the cooling tower makeup. Any significant change could change the order of preference shown above.

(c) As evaporative condensers are not nearly as common in the United States as the conventional cooling tower-condenser systems, there may be some reluctance in accepting this alternative. However, evaporative condensers are more common in other parts of the world.

(d) The "plume" may be objectionable and the client or authority involved may be reluctant to accept anything other than a dry cooling tower or other "plume less" towers not covered in this paper (i.e., wet/dry tower).

(e) There may be a problem with either the water supply or the blowdown disposal. Capital or annual operating costs for coping with a supply or disposal problem could be significant.

(f) Site space limitations may preclude using an air cooled or evaporative condenser simply because of the much larger heat exchange surfaces that are required.

(g) Noise level considerations must be carefully addressed in the specification and purchase of evaporative and air cooled condensers.

Using a spread sheet approach to calculating projected annual operating costs is much more accurate for cost-benefit analyses than use of a single design or average temperature. Cost-benefit calculations using a single temperature resulted in different equipment size selections than indicated by the summary sheets in this paper.

The foregoing should be considered descriptive of the approach to be used in evaluating the various alternatives. Additional work needs to be done in evaluating such other factors not examined as:

(a) The optimum approach temperature for the various pieces of equipment.

(b) The effect of maintenance costs.

(c) Client preferences.

(d) Site specific constraints.

It should also be noted that there is an endless opportunity to improve on the detail of these spread sheets. For example, computer programs are available for the sizing of each type of condenser or cooling tower considered. The program could include specific cost estimating data for each piece of equipment so that the facility cost could be developed for each alternative as the size of a piece of equipment is changed. The complexity of this work is very great and the extent to which it can be justified for the size of plants being considered is questionable.

CONCLUSIONS

Evaluation of different condensing systems at a specific design point may not lead to the proper selection of the optimum type of condensing equipment or even the proper design vacuum to be specified for the type of equipment selected. Rather than utilizing the 1% wet- or dry-bulb temperatures for a comparative evaluation, a calculation of projected annual operating results is recommended. Also, the cost of water, the cycles of concentration possible in evaporative types of heat rejection systems, the cost of chemicals to treat the makeup water and the cost of disposing of the blowdown water will have significant effect on the economic evaluation. All of these factors, as well as site limitations and specific site restrictions concerning plume abatement, noise, etc., must be evaluated for each site to arrive at the optimum selection of the type and size of equipment to be used.

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