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ENERGY DESTRUCTION ANALYSIS OF X-TYPE SHELL AND TUBE SINGLE SEGMENTAL BAFFLE STEAM CONDENSER WITH VARIOUS OPERATING CONDITIONS

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Abstract - A condenser is a two-phase flow heat exchanger in which heat is generated during condensation process which is removed from the system by a coolant. Here key point is energy destruction which always associates with condensation due to difference between condensate temperature and inlet CW temperature. Thus it is very crucial to operate the condenser efficiently under the various operating condition to minimize the energy destruction and enhance energy efficiency. This paper focus on optimization of energy destruction with respect to different condenser pressures, mass flow rate of steam and inlet CW and environment temperatures with strictly taken into account that condensation of the entire vapor must within condenser. To find out the overall heat transfer coefficient, Bell Delaware method is used; all relevant geometric dimensions required are also mathematically found. In first case, it is found that energy destruction decreases with decrease of condenser pressure for given atmospheric condition and inlet CW temperature is also decreases accordingly. So it is better to operate the condenser at as low as possible pressure. In second case if steam mass flow rate increases then energy destruction is also increases and the inlet CW temperature required to be decreases to satisfy the condition of condensation of entire steam. Finally in third case, if coolant flow rate increases for given atmospheric temperature, energy destruction reduces which leads to increases inlet CW temperature.

Keywords - Energy destruction(E_d) ,Energy efficiency ($\eta_{ex)}$ Condenser pressure, steam- coolant flow rate & inlet CW temperature (CW), condensation & condensate.

I. CONCEPT OF ENERGY

Dead state and environment

Energy is a measure of the departure of the state of the system from that of the environment. Thus opportunity for doing useful work exists whenever two systems at different states are placed in communication and principle work can be developed as the two are allowed to come into equilibrium (dead state) . It is the maximum theoretical useful work obtainable as the systems interact to equilibrium

When the pressure, temperature, composition, velocity or elevation of a system is different from the environment, there is an opportunity to extract energy but it diminishes, ceasing to exist when the two, at rest relative to one another, are in equilibrium.

Approach of energy analysis is well suited for furthering the goal of more effective energy resource use, for it enables the location, cause, and true magnitude of waste and loss to be determined and design of new energy efficient system which improving the efficiency of existing systems and also provides insights that elude a purely first-law approach. [1]

Energy Components

In the absence of nuclear, magnetic, electrical, and surface tension effects, the total energy of a system E can be divided into four components: physical

energy E^{PH}, kinetic energy E^{KN}, potential energy E^{PT}, and chemical energy E^{CH},

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH}$$

II. CONDENSER GEOMETRY

Objective of this section is to outline surface geometrical characteristics are, the heat transfer area, minimum free-flow area, frontal area, hydraulic diameter, and flow length on each fluid side of the exchanger. The ratio of free-flow area to frontal area is needed for the determination of entrance and exit pressure losses, flow bypass and leakages for shell-and-tube condenser that are used in the determination of actual heat transfer coefficient and actual pressure drop. [2]

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Schematic diagram

Following X- type single segmental one shell pass, two tube passes condenser is selected for case study.

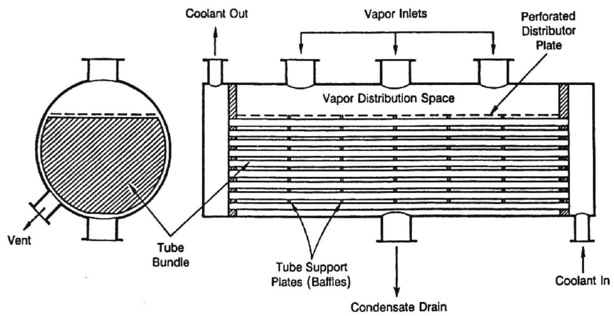

Figure 1 Main Features of a Cross Flow Condenser

Shell-Side Flow Patterns

The plate baffle is to induce cross flow for higher heat transfer coefficients and hence improved heat transfer performance, this objective is not quite achieved in conventional shell-and-tube heat exchanger.

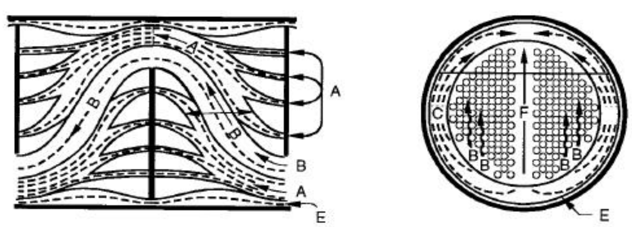

Figure: 2 Shell Side Flow Distributions and Identification of Various Streams

Three clearances associated with a plate baffle are tube-to-baffle hole clearance, bundle-to-shell clearance, and baffle-to-shell clearance. In a multipass unit, the tube layout partitions may create open lanes for bypass of the cross flow stream. [3]

Geometrical Dimensions

For analysis of condenser following geometric dimensions are taken.

Jose M. Ponce-Ortega used genetic algorithms method for optimization of shell and tube heat exchanger They used Bell-Delaware method for the description of the shell side flow and optimize the major geometrical parameters such as number of tube-passes, standard internal and external tube diameters, tube layout and pitch, type of head, fluids allocation, number of sealing strips inlet and outlet baffle spacing, and shell side and tube-side pressure drops. [4]

Table 1: Geometrical Dimensions of Condenser

Shell Side Inside Diameter	D_s	5.1m
Tube-Side Outside Diameter	d_o	25.4mm
Tube-Side Inside Diameter	d_i	22.9mm
Tube Length	L	10m
Total Number of Tubes	N_t	17,350
Number of Tube Passes	N_p	2
Tube Material		Cu/Ni 90/10
Thermal Conductivity of Tube Wall	K_b	45W/m K

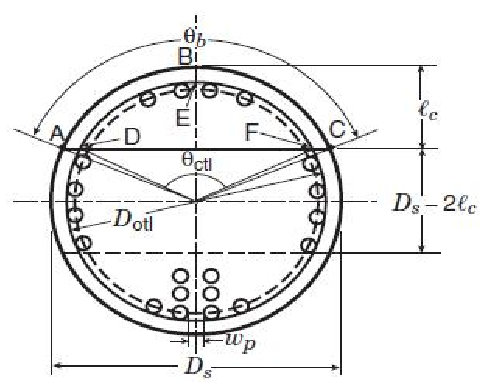

Figure 3: Nomenclatures for Basic Single segmental Baffle Geometry

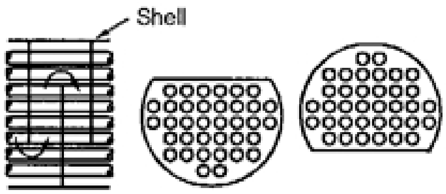

Figure 4: ***Single Segmental*** **Baffle**

V.K. Patel, R.V. Rao carried out the optimization of shell and tube heat exchanger using the new technique called particle swarm optimization. Minimization of total cost is considered as the objective function. Three design variables such as shell internal diameter, outer tube diameter and baffle spacing are considered for optimization. The results of optimization are compared with those obtained by using genetic algorithm. [5] The geometrical information needed for rating an exchanger Bejan demonstrated the use of irreversibility as a criterion for evaluation of the efficiency of heat exchanger to minimize the wasted energy. [6]

III. OPTIMIZATION TECHNIQUES, PROCEDURE AND FORMULATION

Optimization techniques

Y. Haseli carried out the analysis of the shell and tube condenser with respect to energy. They focused on evaluation of the optimum CW temperature during condensation of saturated water vapour within a shell and tube condenser, through minimization of E_d. They derived and expressed the E_d as a function of temperature of CW and solved it using the sequential quadratic programming (SQP) method. [7]

Thermoeconomic optimization of a shell and tube condenser was carried out by Hassan Hajabdollahi; they use two new optimization methods, genetic algorithm and particle swarm method. These methods are used to find out optimal total cost including investment and operation cost. [8].

Optimization procedure

The aim is to establish the inlet CW temperature through minimization of E_d for a known condensation temperature and a given heat transfer area. The importance of condensation of the entire vapor mass flow rate is strictly taken into account. Thus, the E_d subject to the energy balance between cold and hot fluid streams as well as the governing het transfer equation representing the heat released due to the condensation of vapor, removed to the coolant by convective heat transfer. Symbolically, it may be expressed as follows,

Minimize $E_d = f(T_{c1}, T_{c2})$

Subject to $Q = m_s h_{fg} = m_c c_{pc}(T_{c2} - T_{c1})$

$Q = U_o A_{eff} \Delta T_{lm}$, where $T_{c1} \geq 10°C$

Thus, $m_s h_{fg} = U_o A_{eff} \Delta T_{lm}$

Formulation of energy destruction and energy efficiency

Energy destruction is,

$$E_d = m_s\left\{c_{pv}\left[(T_{v1} - T_{cond}) - T_o \ln\left(\frac{T_{v1}}{T_{cond}}\right)\right] + h_{fg|T_{cond}} - T_o s_{fg|T=T_{cond}}\right\} - m_c c_{p,c}\left[(T_{c2} - T_{c1}) - T_o \ln\left(\frac{T_{c2}}{T_{c1}}\right)\right]$$

Note that h_{fg} and s_{fg} are dependent on the saturation temperature. Energy efficiency is,

$$\eta_{ex} = \frac{m_c c_{p,c}\left[(T_{c2} - T_{c1}) - T_o \ln\left(\frac{T_{c2}}{T_{c1}}\right)\right]}{m_s\left\{c_{p,v}\left[(T_{v1} - T_{cond}) - T_o \ln\left(\frac{T_{v1}}{T_{cond}}\right)\right] + h_{fg|T_{cond}} - T_o s_{fg|T=T_{cond}}\right\}}$$

IV. Results and Discussion

Results are obtained for energy destruction based on following different operating conditions.

Table 2: Operating parameters of condenser

Cooling Water Flow Rate	m_c	27000 m^3/hr
Cooling Water Inlet Temperature	t_{c1}	30 °C
Cooling Water Outlet Temperature	t_{c2}	40 °C
Steam Flow Rate	m_s	530 tph
Steam Inlet temperature	t_s	183 °C
Condensate Temperature	t_{cond}	33-45 °C
Operating Pressure	P_c	0.18bar

Case-1 When Condenser pressure varies

It is seem that η_{ex} is negative up to 19°C of the inlet temperature of CW, because at low temperature of CW difference between the CW and environment temperature decreases. Thus ability of the system to carry the energy decreases. With decrease of condenser pressure from 0.18 bar to 0.10 bar optimum CW temperature is also decrease from 34°C to 21°C, and E_d at 21°C decreases from 41755 kW to 30263 kW. So it is better to operate the condenser at as low as possible pressure, as expected.

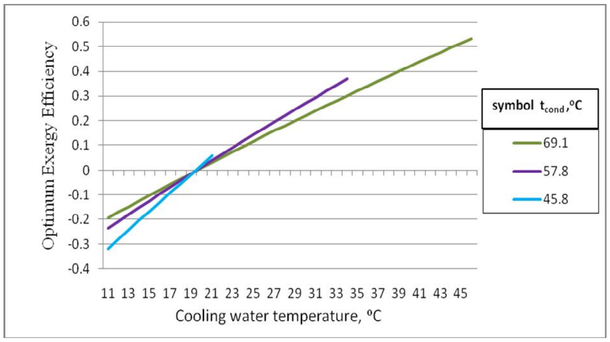

Figure 5: Variation of Energy Efficiency with Cooing Water Temperature at Three Different Condenser Pressures

For given operating condition it is clear that E_d decreases with increase of CW temperature and η_{ex} increases. But increase of the CW temperature results in lower temperature difference between the CW and saturated steam, hence E_d decreases with increase of CW temperature. E_d decreases from 31653 kW to 27350 kW when CW temperature increases from 30°C to 34°C and η_{ex} increases from 27.21% to 31.1%.

Table 3: Results of Energy Destruction and Energy Efficiency with Three Different Condenser Pressure m_s = 530 tph m_c = 27000 tph $t_o = 25°C$

t_{c1}(°C)	P_{cond}=.30bar (t_{cond} = 69.1°C)		P_{cond}=.18bar (t_{cond} = 57.8°C)		P_{cond}=.10bar (t_{cond} = 45.8°C)	
	$E_d(kW)$	η_{ex}	$E_d(kW)$	η_{ex}	$E_d(kW)$	η_{ex}
11	62929	-0.1932	53716	-0.2353	42367	-0.3201
12	61710	-0.1701	52483	-0.2069	41119	-0.2812
13	60499	-0.1471	51258	-0.1788	39880	-0.2426
14	59296	-0.1243	50042	-0.1508	38649	-0.2043
15	58101	-0.1017	48834	-0.123	37427	-0.1662
16	56915	-0.0792	47634	-0.0954	36212	-0.1283
17	55736	-0.0568	46442	-0.068	35006	-0.0908
18	54566	-0.0346	45258	-0.0408	33809	-0.0534
19	53403	-0.0126	44083	-0.0138	32619	-0.0164
20	52248	0.0093	42915	0.0131	31437	0.0205
21	51101	0.0311	41755	0.0398	30263	0.057
22	49962	0.0527	40603	0.0663		
23	48830	0.0741	39458	0.0926		
24	47706	0.0954	38321	0.1188		
25	46589	0.1166	37191	0.1447		
26	45479	0.1377	36069	0.1705		
27	44376	0.1586	34954	0.1962		
28	43281	0.1793	33847	0.2216		
29	42193	0.2	32746	0.2469		
30	41112	0.2205	31653	0.2721		
31	40038	0.2408	30567	0.2971		
32	38971	0.2611	29488	0.3219		
33	37911	0.2812	28416	0.3465		
34	36857	0.3011	27350	0.371		
35	35811	0.321				
36	34771	0.3407				
37	33737	0.3603				
38	32710	0.3798				
39	31690	0.3991				
40	30676	0.4184				
41	29668	0.4375				
42	28666	0.4565				
43	27671	0.4753				
44	26682	0.4941				
45	25699	0.5127				
46	24722	0.5312				

m_s = 530 tph m_c = 27000 tph $t_o = 25°C$

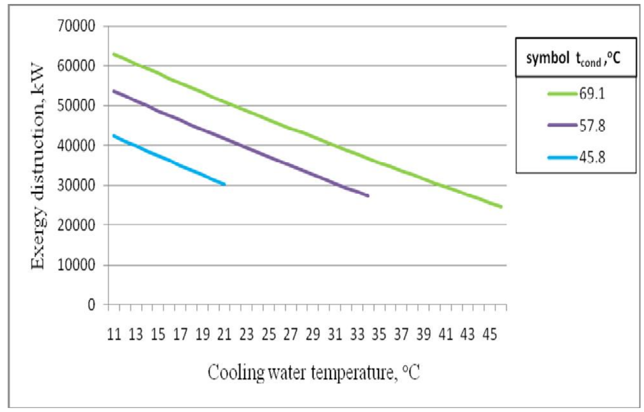

Figure 6: Variation of Energy Destruction with Cooing Water Temperature at Three Different Condenser Pressures

Case-2 When steam mass flow rate varies

Table 4: Variations of Cooling Water Temperature, Energy Destruction and Energy Efficiency with Steam Mass Flow Rate at Three Different Environmental Temperatures

p_{cond} = 0.18 bar (t_{cond} = 57.8°C) m_s = 530 tph m_c = 27000 tph

m_s(%)	t_{c1}(°C)	η_{ex}			E_d (kW)		
		t_o=25°C	t_o=30°C	t_o=35°C	t_o=25°C	t_o=30°C	t_o=35°C
70	53	0.6289	0.591	0.5433	1.37E+04	1.35E+04	1.34E+04
80	51	0.6027	0.5614	0.5092	1.68E+04	1.66E+04	1.64E+04
90	48	0.5581	0.5107	0.4511	2.10E+04	2.08E+04	2.07E+04
100	46	0.5312	0.4803	0.4161	2.47E+04	2.46E+04	2.44E+04
110	44	0.5041	0.4496	0.3808	2.88E+04	2.86E+04	2.85E+04
120	42	0.4768	0.4186	0.3452	3.31E+04	3.30E+04	3.29E+04
130	39	0.4301	0.3657	0.2845	3.91E+04	3.90E+04	3.89E+04
140	37	0.4021	0.3339	0.2479	4.41E+04	4.41E+04	4.41E+04

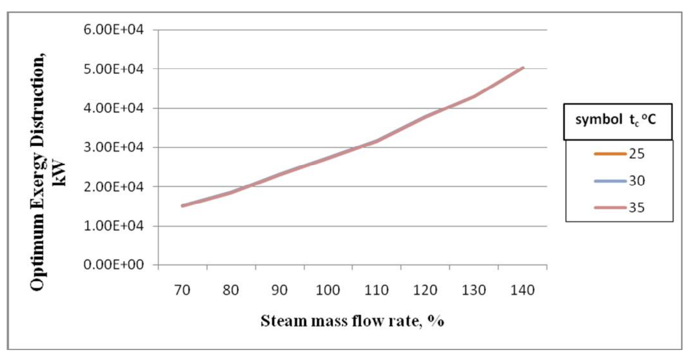

Figure 7: Variation of Minimum Energy Destruction with Steam Mass Flow Rates at Three Ambient Temperatures

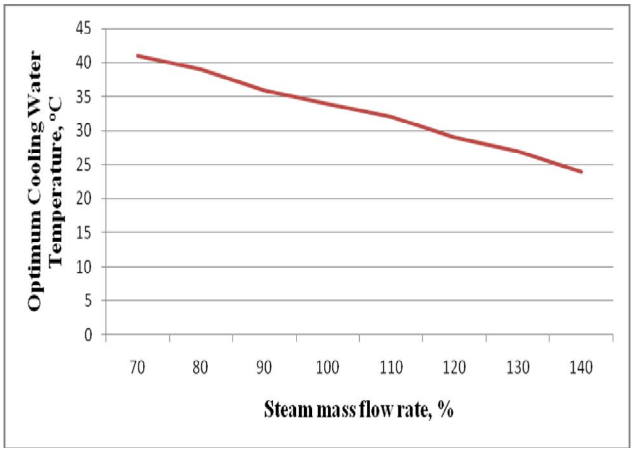

Figure 8: Variation of Optimum Cooling Water Temperature with Steam Mass Flow Rate

When the steam mass flow rate increases, the optimum CW temperature decreases. A higher amount of steam removes more heat due to the latent heat release to the CW, for a constant condenser configuration, conservation of energy implies a higher temperature difference between the condensate and CW, it may be established by reducing the inlet temperature of CW. Increasing the ambient temperature decreases the temperature difference between the CW and ambient condition which results in a higher E_d.

Case-3 When coolant flow rate varies

With increase of mass flow rate of coolant, heat carrying capacity of coolant per °C increases, whereas for constant condenser pressure heat released by steam remains constant, so conservation of energy implies a lower temperature difference between the condensate and CW, thus for lower temperature difference may be established by increasing optimum CW temperature. But at higher mass flow rate of coolant, its effect on optimum temperature decreases, at the end of the graph profile tend to become flatter.

Table 5: Effect of Cooling Water Flow Rate on Optimum Temperature of Coolant, Energy Efficiency and Energy Destruction

p_{cond} =0.18bar (t_{cond} = 57.8°C) $t_o = 25°C$

m_c(%)	t_{c1}(°C)	η_{ex}	E_d(kW)
100	34.6	0.3856	2.67E+04
110	35.4	0.393	2.64E+04
120	36.1	0.3999	2.61E+04
130	36.7	0.406	2.58E+04
140	37.2	0.4108	2.56E+04
150	37.6	0.4141	2.55E+04
160	38	0.4183	2.53E+04
170	38.3	0.4206	2.52E+04
180	38.6	0.4236	2.51E+04

p_{cond} =0.18bar (t_{cond} = 57.8°C) m_s = 530 tph

m_c = 27000 tph $t_o = 25°C$

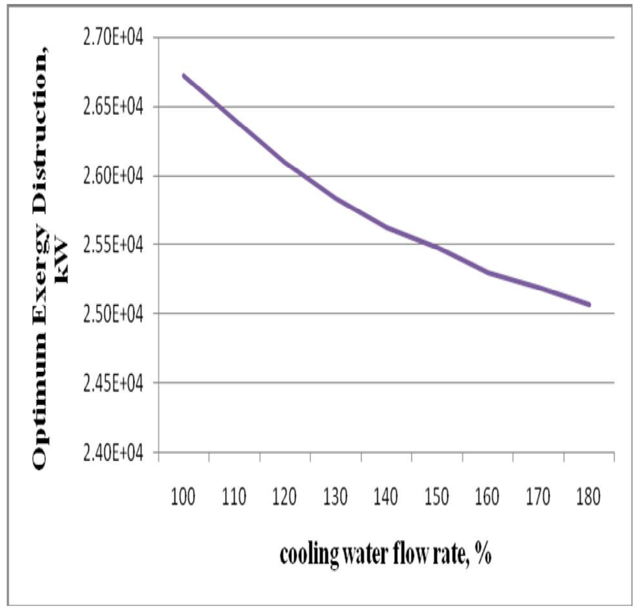

Figure 9: Variation of Minimum Energy Destruction with Cooling Water Flow Rates

As the optimum CW increases with mass flow rate of coolant, thus for given atmospheric temperature, E_d of condenser increases with CW flow rate. At higher mass flow rate of coolant effect of coolant flow rate decreases and profile of graph tends to become flatter.

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