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Energy audit case studies I—steam systems

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Abstract

This paper presents an analytical diagnostic tool for energy audit of steam systems. The circuit efficiency is determined as a product of the segment efficiencies. The analysis is applied to a few industrial cases. These will provide clear indication on the pattern of energy losses and will aid in decision support for evolution of energy conservation measures. The results indicate that contrary to the popular thrust areas, the steam lines and the condensate loss are the major causes of fuel energy wastage and these offer considerable potential for conservation. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Steam circuit; Boiler; Circuit efficiency; Energy conservation

1. Introduction

An energy audit is a technique for identifying energy losses, quantifying them, estimating conservation potential, evolving technological options for conservation and evaluating techno-economics for the measures suggested.

Though the objectives of an energy audit are universally accepted, the methodology is not standardized. In this paper, an attempt is made to standardize the methodology of an energy audit by determining the circuit efficiency as a product of the various sub-system efficiencies. By so doing, losses and efficiencies of each segment in the system can be determined independently. This would provide a clue as to where to act on improving the energy efficiency of the system.

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Nomenclature

APH	Air pre-heater
HHV	Higher heating value (kJ/kg)
LHV	Lower heating value (kJ/kg)
Q	Rate of energy input, output or loss (kW)
SCAPH	Steam coil air pre-heater
SFC	Specific fuel consumption (kg/kg)

Greek letters

η	Efficiency or factor ($0 \le \eta \le 1$)

Subscripts

b	Boiler
c	Combustion
f	Fuel
h	Heat transfer
l	Steam line
m	Material
n	Net energy absorption
o	Overall steam system
r	Condensate recovered
u	Useful task

This paper is devoted to determining the circuit efficiency of the steam system. Use of conversion chain efficiencies for industrial systems and for industrial segments or sub-systems have been proposed with a view to evaluating gross specific energy consumption of a product or service [1,2], but in this paper the conversion chain is used as a diagnostic tool for decision support on energy conservation measures.

A steam system consists of two main units: the steam generator or boiler and the load circuit. Fig. 1 gives a schematic of the steam circuit.

A great deal of information on the generation and utilization of steam, accumulated over this century, is available in the literature. Typically, O'Callaghan [3] has provided a detailed checklist of measures for control of energy consumption in steam systems. Estop and Croft [4] have highlighted energy conservation techniques for steam systems for heat and power applications. Equipment manufacturers like Babcock and Wilcox Company [5] have also documented their experience on the production and use of steam. Based on the above experiences, the factors affecting steam circuit efficiency can be qualitatively classified as follows:

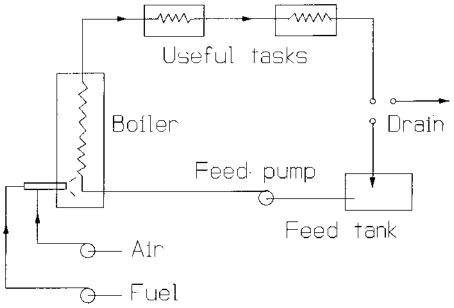

Fig. 1. Schematic of the boiler system.

1.1. Boiler

1.1.1. Combustion

- Furnace pressure (draft)
- Air to fuel ratio
- Atomization efficiency
- Turbulence (mixing)
- Furnace temperature
- Effectiveness of controls

1.1.2. Heat transfer

- Water composition
- Flue gas side resistance
- Geometry/view factor
- Area of heat transfer

1.2. Load circuit

1.2.1. Heat transfer

- Area of heat transfer
- Thermal resistance on the water-steam side
- Steam quality

1.2.2. Dispersion

- Line leakage
- Thermal dispersion
- Pressure drop
- Loss through steam traps
- Loss through deaerator

1.2.3. Condensate/liquid return

- Filtered return for contaminated liquid
- Direct return
- Presence of condensate polishing unit

Ideally, a closed loop feedback control of the useful load by the steam generator is desirable wherein the steam supply responds to the rapid fluctuation in the useful task requirements. In the absence of accurate tracking of the tasks due to lack of communication between the source (steam) and the loads (end tasks), steam is wasted and the various losses will increase thereby increasing the fuel consumption. The quantification of the losses is provided below.

2. Circuit efficiency

The overall steam system efficiency (η_0) is given by,

$$\eta_o = \eta_b \eta_l \eta_u / \eta_r \tag{1}$$

where η_b is the boiler efficiency, η_l is the efficiency of the steam line, η_u is the useful task efficiency and η_r is the factor of un-recovered condensate.

The boiler efficiency (η_b) is given by,

$$\eta_b = \eta_c \eta_h \eta_m \tag{2}$$

This is composed of combustion efficiency (η_c), heat transfer efficiency (η_h) and the material efficiency (η_m) which are given as follows:

$$\eta_c = Q_h / Q_f \tag{3}$$

where Q_h is the energy in hot flue gas delivered from the fuel and Q_f is the energy in the fuel supplied to the boiler. The combustion efficiency determines what fraction of the energy in the fuel is converted into thermal energy. It accounts for losses due to unconverted or partially converted fuel in ash, fuel rejects and in flue gases.

$$\eta_m = Q_n / Q_h \tag{4}$$

where Q_n is the net energy absorbed by the water-steam in the boiler. The material efficiency accounts for energy losses due to physical loss of water/steam due to continuous blow down, intermittent blow down, venting from boiler drum, release of pressure relief valves in the boiler, extraction of steam from boiler before main steam outlet for steam jet ejectors, water treatment plant, etc. The optimal concentration of contaminants for steam generation in the complete pressure range is available as curve fits [6]. Maintaining more conservative concentration of contaminants leads to excessive blow down losses.

$$\eta_h = (Q_b - Q_r)/Q_n \tag{5}$$

where Q_r is the energy in condensate recovered from the condensate return and Q_b is the energy in the steam at the boiler outlet. The heat transfer efficiency determines what fraction of the thermal energy in flue gas is actually transferred to the water and steam in the boiler. It is a rate process primarily controlled by the heat transfer coefficients, area of contact and the temperature difference between the flue gas and the water/steam. Cleanliness of the heat transfer surfaces and the hydrodynamics also affects the heat transfer efficiency.

The boiler efficiency (which is a product of the above three efficiencies) is given by

$$\eta_b = (Q_b - Q_r)/Q_f \tag{6}$$

As a whole, the boiler efficiency represents the transfer function relating the fuel consumption rate to the steam generation rate.

The efficiency of the steam line (η_l) is given by

$$\eta_l = (Q_b - Q_l)/Q_b \tag{7}$$

where Q_l is the energy loss in the line due to heat dissipation from the surface of pipelines, water loss (operation of steam traps, drips, leakage, etc.) and steam loss (venting, leakage, etc.). The line losses include loss in the main steam line and the return line (after completion of the useful tasks).

The useful task efficiency (η_u) is given by

$$\eta_u = Q_u/(Q_b - Q_l) \tag{8}$$

where Q_u is the theoretical useful energy required to accomplish the intended tasks. The useful efficiency determines what fraction of the steam available to it (at the useful task point) is actually utilized. It determines the quantity of energy lost due to poor geometric configuration of the task set up, inefficient tracking of the useful tasks by the steam flow (poor control of the useful load by the steam source), surface heat loss of end task equipment and steam condensation in the heat transferring chambers of the useful tasks, etc.

The factor of un-recovered condensate is given by

$$\eta_r = (Q_b - Q_r)/Q_b \tag{9}$$

It is a common practice in industry to drain away the hot condensate either because of an apprehension of contamination or because liquid lines are not available. The factor of un-recovered condensate represents the energy losses due to physical draining of condensate out of the system, escape of steam-air mixture from the ejector exhaust, from the deaerator, etc.

The overall utilization efficiency of the steam is given by

$$\eta_0 = Q_\mathrm{u}/Q_\mathrm{f} = [Q_\mathrm{h}/Q_\mathrm{f}][Q_\mathrm{n}/Q_\mathrm{h}] \times [(Q_\mathrm{b} - Q_\mathrm{r})/Q_\mathrm{n}] \times [Q_\mathrm{b}/(Q_\mathrm{b} - Q_\mathrm{r})] \times [(Q_\mathrm{b} - Q_\mathrm{l})/Q_\mathrm{b}] \times [Q_\mathrm{u}/(Q_\mathrm{b} - Q_\mathrm{l})] \tag{10}$$

Substituting the respective efficiencies, Eq. (10) is a proof of Eq. (1).

The overall utilization efficiency is a transfer function relating the final energy in steam utilized to the fuel input to the system.

3. Results and discussion

The performance of boilers can be characterized by the boiler efficiency, steam to fuel ratio and specific steam consumption. Table 1 gives some typical values of these for various power and process boilers based on experimental measurements obtained from a wide range of boilers tested.

The boiler efficiency for a coal fired boiler is given in Table 2. The efficiency of oil and gas fired boilers is given in Tables 3 and 4. The data in Tables 3 and 4 are based on actual tests conducted in power cum process boilers. The controllable losses are the dry flue gas losses (due to high exhaust temperature and excess air flow), unconverted or partially converted fuel in ash and exhaust and furnace skin radiation.

Typical circuit efficiency of two oil fired boilers is given in Table 5. The following observations can be made from the above mentioned table:

1. The steam line losses and loss of un-recovered condensate are major causes for decrease in the overall system efficiency. These losses can be minimized by ensuring that the steam at the boiler outlet is superheated and that the condensate is sub-cooled sufficiently. The presence of water or wet (moisture laden) steam in the main steam line and presence of

Table 1
Typical values of performance indices of power and process boilers

Sl. No.	Particular	Process boilers			Power boilers		
		Oil	Gas	Coal	Oil	Gas	Coal
01	Boiler efficiency (%)	65–85	60–70	20–50	80–92	70–78	75–86
02	Steam to fuel ratio (t/t)	10–15	13–14	4–6	12–16	14–16	5–6
03	Specific steam consumption (t/MWh)	6.0–15.0			3.0–6.0		
04	Air to fuel ratio (theoretical)	14–15	12–13	5–7	14–15	12–13	5–7
05	Excess air (% of theoretical air)	2–100	2–30	100–400	2–20	2–20	25–300
06	Heat to power ratio ($\mathrm{MW_t/MW_e}$)	0.5–40.0			0.0–0.2		

Table 2
Results of the boiler efficiency test on a coal fired boiler

Sl. No.	Particular	Unit	Design (210 MW)	Operating (172.8 MW)
Combustion related losses				
01	Loss due to hydrogen in the fuel	%	5.15	6.63
03	Loss due to moisture in fuel	%	0.00	0.96
03	Loss due to moisture in air	%	0.22	0.23
04	Loss due to unburnt fuel in bottom ash	%	1.00	0.25
05	Loss due to unburnt fuel in fly ash	%	1.00	0.98
Heat transfer related losses				
06	Heat equivalent of auxiliary power	%	0.00	−0.65
07	Dry flue gas loss	%	4.95	7.25
08	Loss due to furnace skin radiation and convection	%	0.21	0.11
Material related energy losses				
09	Blow down losses	%	0.00	0.52
10	Venting and losses	%	0.50	0.50
11	Extraction steam losses	%	1.00	0.00
12	Total losses	%	14.02	16.78
13	Combustion efficiency	%	92.64	90.95
14	Heat transfer efficiency	%	94.84	93.29
15	Material efficiency	%	97.86	98.08
16	Boiler efficiency	%	85.98	83.22
17	Heat input rate	MW_t	542.54	446.46
18	Heating value of coal			
	Based on ultimate analysis	MJ/kg	17.81	15.29
	Based on operating HHV		–	13.67
19	Theoretical flame temperature			
	Based on theoretical fuel composition	°C	–	1507.9
	Based on operating HHV		–	1350.3
20	Steam to fuel ratio	t/t	5.08	3.80
21	Oxygen (measured) before APH[a]	%	4.20	6.70
	Oxygen (measured) after APH	%	6.20	9.70
22	Air in-leakage	t/h	80.00	247.10
23	CO before APH	ppm	120	210

[a] APH: air pre-heater.

steam in the return line (after the useful tasks) leads to line losses. Improving dryness by throttling steam is not a solution and instead, the focus is to produce superheated steam at the boiler outlet.

2. The overall system efficiency is only around 26–30%, which is vastly different from the boiler efficiency.
3. The boiler efficiency is bifurcated as combustion efficiency, heat transfer efficiency and the material efficiency. It is our frequent observation that when boiler efficiencies are low, an attempt is made to improve only the combustion efficiency. The heat transfer efficiency is

Table 3
Results of the boiler efficiency tests on an oil fired boiler

Sl. No.	Particular	Unit	Design	With SCAPH[a]	Without SCAPH
Combustion related losses					
01	Loss due to hydrogen in the fuel	%	6.78	7.97	7.98
03	Loss due to moisture in fuel	%	0.01	0.07	0.06
03	Loss due to moisture in air	%	0.20	0.19	0.20
04	Loss due to unburnt fuel in bottom ash	%	0.00	0.00	0.00
05	Loss due to unburnt fuel in fly ash	%	0.00	0.00	0.00
Heat transfer related losses					
06	Heat equivalent of auxiliary power	%	−0.20	−0.85	−0.27
07	Dry flue gas loss	%	8.70	10.39	9.52
08	Loss due to furnace skin radiation and convection	%	0.62	0.07	0.07
Material related energy losses					
09	Blow down losses	%	0.00	0.30	0.29
10	Venting and losses	%	0.00	0.07	0.13
11	Extraction steam losses	%	0.48	0.63	0.57
12	Total losses	%	16.59	18.84	18.55
13	Combustion efficiency	%	93.01	91.77	91.76
14	Heat transfer efficiency	%	90.88	90.39	90.68
15	Material efficiency	%	98.68	97.84	97.88
16	Boiler efficiency (LHV basis)	%	90.20	93.19	90.49
17	Boiler efficiency (HHV basis)	%	83.41	81.16	81.45
18	Heat input rate	MW_t	–	98.41	97.17

[a] SCAPH: Steam coil air pre-heater.

> ignored. As a result, the desired conservation will not be forthcoming. By clear segregation of combustion efficiency, heat transfer efficiency and material efficiency, a thrust can be given to improving the boiler efficiency by an increase of heat transfer area or the overall heat transfer coefficients, or by a decrease of the material losses. Decreased boiler efficiency due to excessive blow down and excessive draining of main steam for auxiliary tasks is a frequent occurrence.

Based on experimental measurements in a number of steam systems, the range of efficiencies of various circuits have been computed. These are given in Table 6. The achievable efficiencies as best practice in industries are also shown in the table. It can be seen that condensate recovery has a strong effect on minimizing the fuel consumption. Also, useful task efficiency improvement is a potential segment where conservation is feasible.

Th specific fuel consumption (SFC) which is the fuel required to produce a unit of steam is shown at different points in the circuit in Table 7. It is seen that the SFC increases as one moves from the fuel combustion segment to the utilization point. There is value addition to the steam as it moves along the conversion chain. It is thus seen that conservation of one unit of steam at the end use point results in much more energy conservation than increase of the

Table 4
Results of boiler efficiency tests on the same boiler with oil and gas

Sl. No.	Particular	Unit	Design	Natural gas	Fuel oil
Combustion related losses					
01	Loss due to hydrogen in the fuel	%	4.09	13.57	6.49
03	Loss due to moisture in fuel	%	0.19	2.91	0.00
03	Loss due to moisture in air	%	0.00	0.27	0.29
04	Loss due to unburnt fuel in bottom ash	%	0.00	0.00	0.00
05	Loss due to unburnt fuel in fly ash	%	0.00	0.00	0.01
Heat transfer related losses					
06	Heat equivalent of auxiliary power	%	0.00	−0.90	−0.92
07	Dry flue gas loss	%	4.70	5.61	5.94
08	Loss due to furnace skin radiation and convection	%	0.32	0.18	0.25
Material related energy losses					
09	Blow down losses	%	0.25	0.25	0.25
10	Venting and losses	%	0.25	0.25	0.26
11	Extraction steam losses	%	0.50	0.54	0.48
12	Total losses	%	10.30	22.68	13.07
13	Combustion efficiency	%	95.72	83.25	93.21
14	Heat transfer efficiency	%	94.98	95.11	94.73
15	Material efficiency	%	98.66	97.65	98.45
16	Boiler efficiency (HHV basis)	%	89.70	77.32	86.93
17	Heat input rate	MW_t	–	141.37	122.13

boiler efficiency. This fact is a pointer in energy audits where techno-economics of alternative schemes will have to be evaluated. A summary of the energy conservation solutions for improving the efficiencies of various sub-systems is given in Table 8.

4. Conclusions

The main conclusions of the study are as follows:

1. The whole focus in energy audit is on improving the boiler efficiency. It can now be seen that the most important losses are occurring in the steam line and loss of un-recovered condensate. These segments of the steam circuit offer considerable scope for energy recovery and fuel saving.
2. By dividing the boiler efficiency into combustion efficiency, heat transfer efficiency and material efficiency, the diagnosis of the causes of poor efficiency will be more directional, and improvements can be quite dramatic. High flue gas losses and skin losses are caused by poor heat transfer efficiency.
3. The circuit efficiency technique has been successfully used as an effective tool in energy auditing, to identify areas of energy conservation.

Table 5
Experimental efficiencies for two process boilers and their steam circuit

Sl. No.	Particular	Industry No. 1		Industry No. 2	
		Thermal energy (kW)	Efficiency (%)	Thermal energy (kW)	Efficiency (%)
01	Thermal energy in steam[a]	8751.2	–	3257.9	–
02	Energy input to system[b]	10430.4	100.0	3622.5	100.0
03	Combustion efficiency		94.3		92.7
	Energy loss in combustion	594.5		264.4	
04	Heat transfer efficiency		89.6		88.4
	Thermal energy loss in boiler	1084.7		420.2	
05	Material efficiency				
	Energy losses due to water-steam losses				
06	Boiler efficiency		84.5		81.9
	Total energy loss in boiler	1679.2		684.6	
07	Steam line efficiency		79.1		78.6
	Energy loss in main line[c]	1027.9		421.2	
	Energy loss in return line[c]	801.0		207.5	
08	Useful task efficiency		39.4		37.8
	Theoretical energy requirement for performing useful task	2753.5		1039.6	
	Thermal loss in end use equipment	4168.8		1269.6	
09	Un-recovered condensate factor		100.0		84.9
	Heat in condensate recovered	–		320.0	
10	Overall circuit efficiency	–	26.4%		28.7%

[a] Steam generating capacity: Industry No. 1 = 12.20 t/h; Industry No. 2 = 3.9 t/h.
[b] Fuel consumption: Industry No. 1 = 847.0 kg/h; Industry No. 2 = 288.4 t/h.
[c] Includes surface heat loss plus leakage plus loss through steam traps.

Table 6
Typical efficiencies for process boilers and steam circuits

Sl. No.	Particular	Range (%)	Best practice (%)
01	Efficiency: combustion	90.0–94.0	95.0
02	Efficiency: heat transfer	90.0–95.0	96.0
03	Efficiency: material	97.0–98.0	99.0
04	Efficiency: boiler	76.5–86.0	90.0–95.0
05	Efficiency: steam line	70.0–80.0	90.0
06	Efficiency: useful task	35.0–60.0	70.0
07	Unrecovered condensate factor	84.0–100.0	80.0
08	Efficiency: overall circuit	12.0–42.0	64.0–67.5

Table 7
Typical specific fuel consumption for steam circuit elements

Sl. No.	Particular	Range (kg/kWh)	Best practice (kg/kWh)
01	SFC: Flue gas	0.090–0.085	0.084
02	SFC: Steam at boiler outlet	0.100–0.092	0.085
03	SFC: Steam at task end point (no condensate recovery)	0.660–0.190	0.148
04	SFC: Steam at task end point (with condensate recovery)	0.560–1.160	0.100

Table 8
Solutions for improvement in steam system component efficiencies

Sl. No.	Particular
01	Combustion efficiency Control of excess air from air fans, illegal ingress in the furnace and from in-leakage in the air pre-heater Improvement in atomization efficiency of gas/oil/liquid fuels or pulverization efficiency of coal/solid fuels Maintaining optimal temperature and pressure of oil and air injected into the burners Contaminant control in fuel and air inputs to the furnace will ensure higher carbon conversion efficiency Improvement in furnace turbulence to ensure mixing of fuel and secondary air by maintaining adequate wind box to furnace differential pressure Improvement in ejection geometry of fuel and air to ensure that they mix within the combustion chamber Ensuring that the fireball is centred and neither unsymmetric not impinging on water tubes Ensuring that the furnace draft is slightly negative and close to atmospheric pressure to avoid either back firing (positive draft) or furnace ingress (excessive negative draft) Ensuring that the burner has a high enough turn down ratio (1 : 7 or so) to handle load fluctuations
02	Heat transfer efficiency Ensuring adequate heat transfer surface Maintaining high cleanliness on the furnace and water sides by on line and off line cleaning schedules Minimizing furnace skin radiation
03	Material efficiency Minimizing loss of steam through blow down, venting, frequent lifting of pressure relief valves, etc. Minimizing loss through blow down by optimal contaminant control Replacing use of high pressure live steam with low grade steam for steam jet ejection, deaerator pegging, steam coil air pre-heater, etc.
04	Steam line efficiency Ensuring that only superheated steam enters the main line and sub-cooled liquid enters the return line after the useful tasks Minimizing steam loss through steam traps by choice of appropriate traps
05	Useful task efficiency Ensure adequate surface area for heat transfer Minimizing bypass of useful steam into drain when there is no useful load (in intermittent operating systems or batch processes) Shorter processing time, accurate control of temperature and flow of steam into end task equipment

(continued on next page)

Table 8 (*continued*)

Sl. No.	Particular
	Minimizing losses from seals, glands, drains, vents, etc., of end use equipment
	Ensuring effective deaeration of steam at the deaerator thereby reducing wetness, increasing heat transfer rate and elimination of air blanketing at the useful task end
06	Unrecovered condensate factor
	Ensuring that all condensate is recycled
	Use of filters for condensate which is in indirect contact (heat exchangers) with oils
	Chemical treatment of condensate in deaerator or use of condensate polishing unit to minimize contaminants
	Minimizing steam/water loss from deaerator steam-air venting, ejector steam-air venting drains, flash steam, etc.
07	Overall circuit efficiency
	Accurate tracking of useful task loading levels by the steam generator output
	Automation of sub-systems such as blow down, burner operation, combustion controls, feed pump pressure control, load management, soot blowing, etc.
	Use of seating materials with improved erosion resistance to ensure that drain valves, balancing valves and recirculation valves do not pass steam when closed
	Use of reverse osmosis water treatment plants in place of ion exchangers can minimize water losses in the entire system

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