AN APPLICATION OF SAFETY ANALYSIS TECHNIQUE FOR THERMAL OPTIMIZATION OF A PAPER MACHINE

by

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This investigation proposes a systematic framework based on the Fault Tree analysis, for the energy and exergy optimization of a paper machine. In the first step, energy and exergy analysis was performed on the dryer section and its related steam and condensate system, to assess the existing performance of paper machine. In the next step, checklists were developed for the identification of key safety and operational issues related to the steam and condensate system. Then, a fault tree analysis was applied to make out and resolve the root causes. Corrective actions were taken in order to rectify various problems. As a result, energy and exergy efficiencies of the system increased by 22% and 14%, respectively. Moreover, an improvement in steam and condensate recovery system was observed.

Key words: *Fault Tree analysis, energy, exergy, optimization, paper machine*

Introduction

Pulp and paper industry has been marked as the third principal user of industrial energy [1]. It has been estimated that around 2/3 of the total energy consumption in pulp and paper industry acts as fuel for the production of heat while the remaining energy is consumed by electricity [2]. As energy prices have ever escalating trend, optimum energy utilization is indispensable.

Paper is an aqueous set down of plant strands in sheet formation [3]. This transformation consists of four unit operations.

(1) Feed preparation where right proportions of different chemicals are mixed with pulp to develop desired properties in paper.
(2) Wire section causes the removal of water from the feed by gravity and vacuum.
(3) Press section improves solid contents to 33 to 55% by compression depending upon the grade of the paper.
(4) Dryer section removes water to generate paper with 5-9% moisture. This section can be subdivided into pre and post drying, if coating is to be done.

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Dryer section is the largest energy consumer in the non-integrated paper mill where pulp and paper making are two distinct departments. Conventionally, contact drying by multiple cylinders/drums heated by steam is used for drying paper and board. It stands for more than 80% of the total steam use [2].

The steam and condensate system depicts an integrated system which is responsible for the supply of saturated steam to the various pulp and paper making processes and recovery of condensate. Three fundamental parts can be identified for such systems: (1) output, (2) transfer, and (3) receiving elements. Each component loses energy and contributes to the decreased efficiency of the system. Several studies have been conducted about the thermal performance of steam systems including their individual elements. Drying section is an important receiving element which influences the efficiency of the steam and condensate system [4].

Acting as a complement to the material and energy balance, exergy balance provides a general and in depth view of the process for potential improvements. Exergy analysis has been investigated as a powerful tool for analysing and improving the pulp and paper mills. This concept offers an important assessment of emissions and waste flows [5].

Fault Tree analysis (FTA) is a powerful rational and deductive technique for analyzing the system operation, safety and elucidating the causal relations leading to a given unwanted event. It is a systematic approach to enumerate malfunctioning of process ingredients and examined symptoms diagrammatically. Thus, it helps to explicate the mechanism of an undesired happening due to a fault or a combination of faults and failures [6, 7]. The contemporary work is a case study of a leading paper and board mill in Pakistan. The specific objective of this case study is to sort out operational problems related to steam consumption and condensate recovery using fault tree analysis approach.

Systematic framework based on FTA

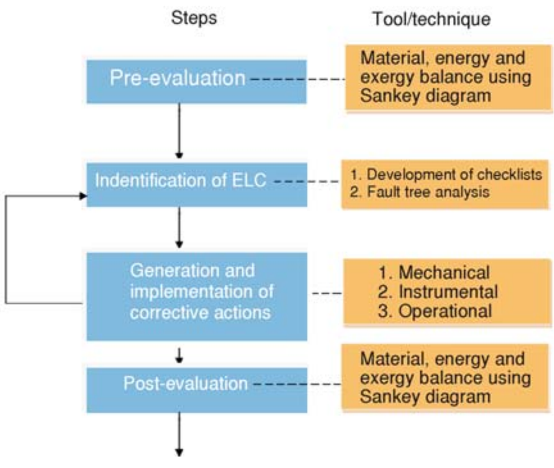


Figure 1. Systematic frame work for thermal optimization using FTA

The systematic approach to perform optimization on paper machine has been indicated in fig. 1.

Step-1 – Pre-evaluation

In this step detailed material, energy and exergy balance was performed to record the initial status of the paper machine represented by Sankey diagram. Since, there was no chemical reaction taking place in the system under investigation, physical exergy (eph) was estimated. eph can be defined as the work achievable by taking a material from its initial state to the state of environment, reversibly [8].

Step-2 – Identification of energy loss contributing factors

In this phase, daily and weekly checklists were developed for monitoring. Major energy loss contributing factors (ELC) were identified based on observations of these checklists.

Step-3 – Generation and implementation of corrective actions

The problems were regularly identified and rectified through the enforcement of corrective actions following the pattern of fig. 2.

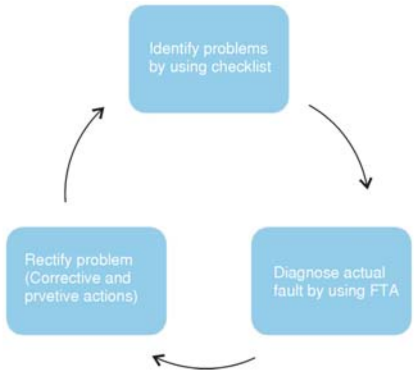


Figure 2. Process of generation of corrective actions based on FTA on ELC

Step-4 – Post-evaluation

After the implementation of corrective actions, paper machine was evaluated on the basis of energy and exergy balance to observe any improvement. In case of decrease in performance, step -2 was re-considered.

Case study

Dryer section of a paper and board mill was taken as a case study (CS) for thermal optimization. Figure 3 illustrates a conceptual diagram of the main material streams around the dryer section. B_1 and B_2 denote the sheet of board with moisture contents entering and leaving the dryer section. S represents the steam entering to the dryer section. This stream converts into three parts viz: M, C_1, and C_2 *i. e.*, water evaporated, condensate and steam wasted, respectively.

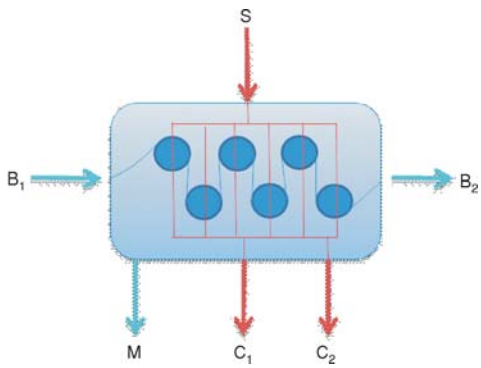


Figure 3. Conceptual layout of the dryer section with respect to material, energy, and exergy flow

CS-Step-1 – Pre evaluation

To commence the thermal optimization on the dryer section of the paper machine, energy balance was performed as shown in fig. 4(a). It indicates steam as the dominant carrier of energy. However, a noticeable energy was carried by the fibres and moisture of the paper machine. Total energy input to the dryer section was found to be 31940 MJ based on one hour operation. In the dryer, steam gives up heat to form condensate. In this case, the condensate stream corresponds to 6801 MJ. The approximated value of energy wasted was 17151 MJ. In addition to energy balance, exergy analysis was performed to illustrate the effective energy balance as shown fig. 4(b).

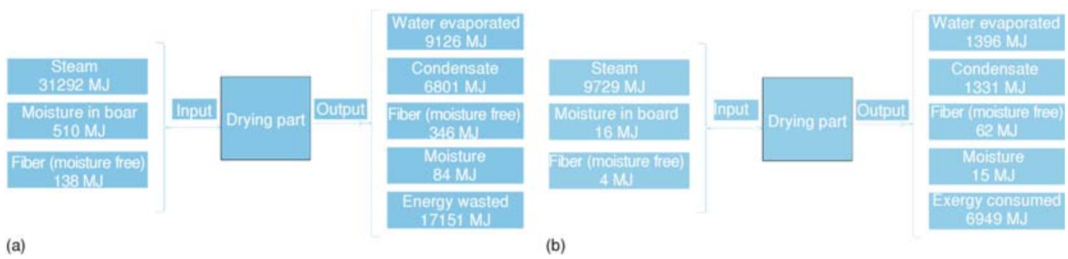


Figure 4. Energy balance on dryer part before optimization (Sankey diagram)

Total exergy lost before optimization was found to be 6946 MJ. Exergy was calculated by the following expressions [5]:

$$e_{\mathrm{ph}} = c_p (T - T_{\mathrm{o}}) - T_{\mathrm{o}} \left(c_p \ln \frac{T}{T_{\mathrm{o}}} - R \ln \frac{P}{P_{\mathrm{o}}} \right) \tag{1}$$

$$e_{\mathrm{ph}} = c_p \left[(T - T_{\mathrm{o}}) - T_{\mathrm{o}} \ln \frac{T}{T_{\mathrm{o}}} \right] - v_m (P - P_{\mathrm{o}}) \tag{2}$$

where e_{ph} is the physical exergy, also recognized as thermomechanical exergy. c – the specific heat of water or board, v_{m} – the specific volume estimated at T_{o}, T and P – the initial temperature and pressure, and T_{o} and P_{o} – the temperature and pressure of environment.

Equation (1) was used to estimate the exergy of the vapour/gas phase (steam) assuming to be ideal gas. To calculate exergy of liquid (water) and solid (board) phases, eq. (2) was used with the assumption that specific heat of the respective phase remains constant throughout the process of drying.

CS-Step-2 – Identification of ELC

To identify crucial problems daily and weekly checklists were implemented in critical areas. Samples of checklist have been given in tables A and B. In these checklists, key points were identified where steam and condensate leakages were observed.

On thorough investigation, following major problems were identified:
- steam/condensate leakages,
- pressurized (abnormal) tanks, and
- improper dryer heating.

CS-Step-3 – Generation and implementation of corrective actions

In this phase problems were investigated to identify root causes. For this purpose FTA technique was adopted. Nature of these problems could be mechanical (*e. g.* damaged equipment), instrumental (*e. g.* inefficient control system) or operational (*e. g.* extra steam pressure). Problem was rectified by resolving actual fault. Hence a working strategy was developed in which first of all problem was identified on regular basis (by using check lists) followed by identification of actual fault (by using FTA) and then problem was rectified by taking necessary corrective and preventive actions.

Table 1. List of major problems found at paper machine

No.	Problems
1	Safety valve of main steam header blowing
2	Safety valve of pre dryers blowing
3	Safety valve of Yankee dryer blowing
4	Steam wastage from vent valves
5	Condensate wastage from drain valves
6	Pressurized main condensate tank (steam passing with condensate)
7	Pressurized intermediate condensate tank (steam passing with condensate

With reference to this problems, seven cases were identified as listed in tab. 1. For each case, an FTA chart was made as shown in figs. 5-11. As a sample, the case of pre-dryer's safety valve has been discussed in detail.

Figure 6 indicates the FTA regarding blowing of pre dryer's safety valve. It may correspond to two situations, viz: (1) blowing of safety valve at lower pressure than its set value due mechanical problem, (2) improper steam utilization resulting in building

A. Observations for optimization – daily inspection sheet

Equipment	Position	Initial status (OK/Not OK)	Corrective action	Final status (OK/Pending)	Remarks
Safety valves	Main steam header				
	Pre dryer top				
	Pre dryer bottom				
	Yankee				
Vent valves/ differential valves	Pre dryer top				
	Pre dryer bottom				
	Yankee				
	Post dryers top				
	Post dryers bottom				
Drain valves	Main condensate tank				
	Pre dryer top tank				
	Pre dryer bottom tank				
	Yankee tank 1				
	Yankee tank 2				
	Post dryers top tank				
	Post dryers bottom tank				
Over pressurized tanks	Main condensate tank				
	Pre dryer top tank				
	Pre dryer bottom tank				
	Yankee tank 1				
	Yankee tank 2				
	Post dryers top tank				
	Post dryers bottom tank				
Flexible pipes	All dryers				
Rotary joints	All dryers				

up of back pressure. The situation may arise due to malfunctioning of any of the paper machine's part *i. e.*, head box, wire, press or dryer section. The problems may be low drying rate, high inlet moisture at drying part and sudden reduction in steam load due to sheet brake. The main reason of low drying rate can be the accumulation of condensate in the dryers. This happens when siphon of the dryer is not working properly or condensate experiences back pressure from the condensate tank. Pre dryer safety valve may blow due to the abnormal high steam requirement. This condition may be faced when the sheet coming to dryer section constitutes high moisture contents. A typical reason for this predicament is the reduced efficiency of the felt in-

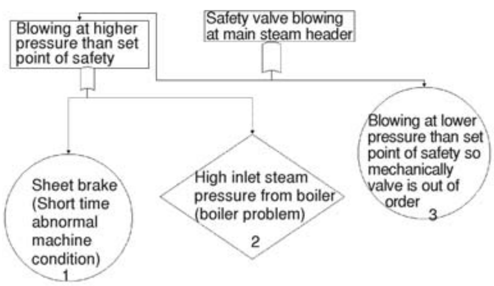


Figure 5. FTA of problem 1 for blowing of main steam header safety valve

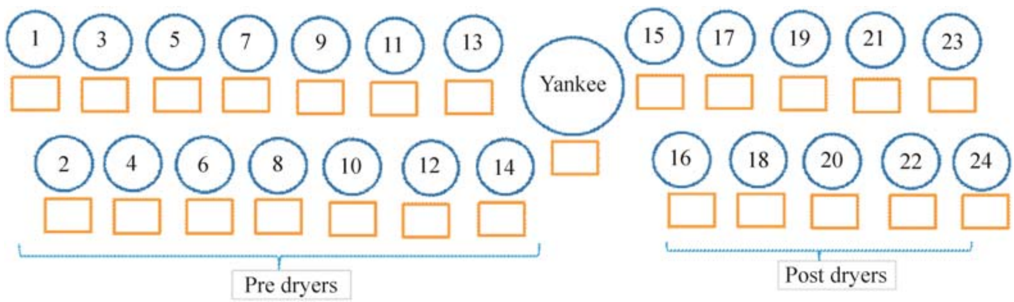
B. Observations for optimization – Weekly inspection sheet; Dryers temperature profile

Date: ____________ Time: ___________

Pressure [bar]	Pre dryers top	
	Pre dryers bottom	
	Yankee	
	Post dryer top	
	Post dryer bottom	
Presses loads	1st press	
	2nd press	
	3rd press	

Ambient temperature [°C]	
Product	
Grammage [gm^{-2}]	
Machine speed [m/min]	

Temperature profile of dryers



dicating the need of new felt. Process conditions may not be ignored as low press and improper mechanical drying of felt may also lead to the high moisture contents.

After root causes analysis based on FTA following corrective actions were taken.

– Before optimization there was a practice of draining condensate after each shutdown (for good heating at startup). This practice is changed and at each shutdown condensate is

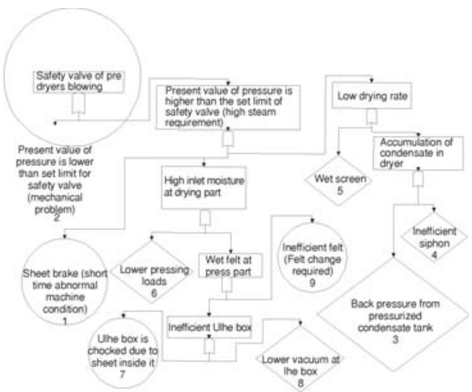


Figure 6. FTA of problem 2 for blowing of pre dryer safety valve

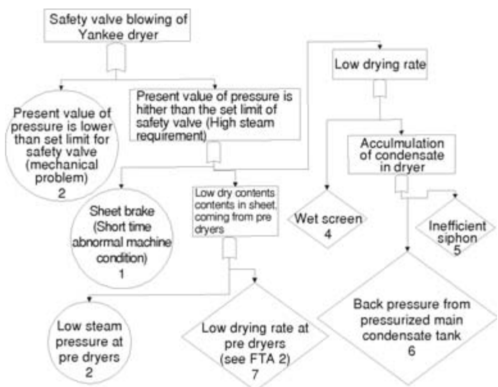


Figure 7. FTA of problem 3 for blowing of Yankee dryer safety valve blowing

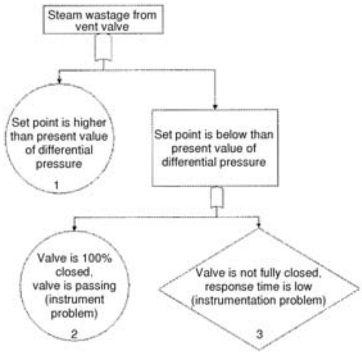


Figure 8. FTA of problem 4 for wastage of steam from vent valves

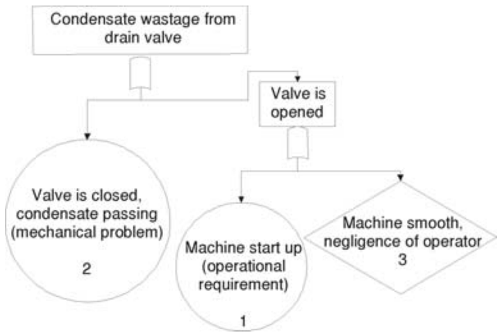


Figure 9. FTA of problem 5 for condensate wastage from drain valves

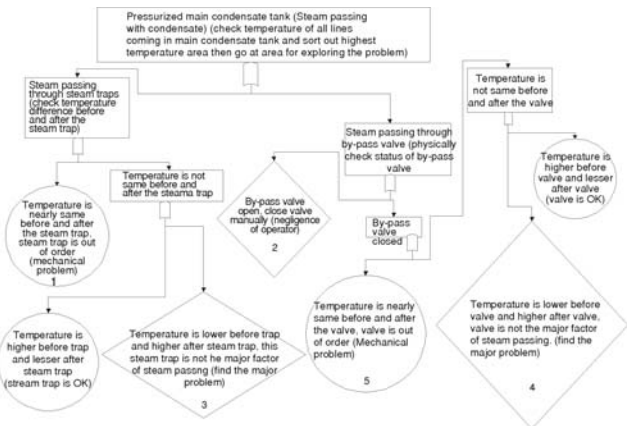


Figure 10. FTA of problem 6 for pressurized main condensate tank

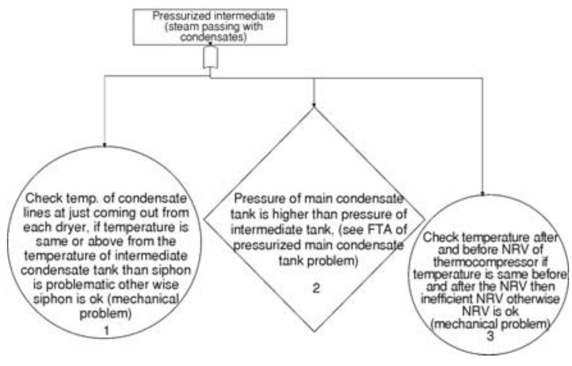


Figure 11. FTA of problem 7 for pressurized intermediate condensate tank

"pumped back" to Boiler House till the system is not able to transfer remaining small quantity of condensate.

– Improper temperature measurement method (*i.e.* Non-contact temperature measurement) for estimation of dryer's temperature was in used which lead to wrong estimation of dryer's condition. (This method has some limitations of proper angle and non-shiny surface). So contact measuring method is introduced to know actual temperature of dryer.
– One steam trap at a pressurized line was missing, so it was installed.
– Improper working of level sensors due to low conductivity of hot water was figured out and this factor was eliminated.
– Insulations on some hot lines were missing. So insulations were installed at those lines to prevent heat losses.

CS-Step-4 – Post- evaluation

After implementation of aforementioned corrective actions an improvement was observed in various parameters of the paper

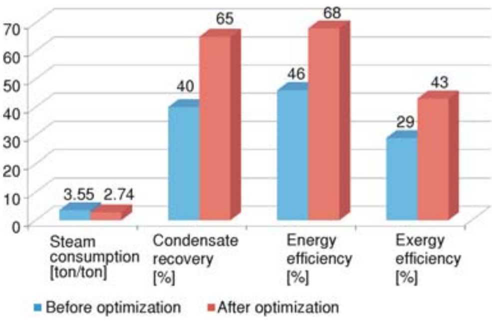


Figure 12. Comparison of steam consumption, condensate recovery, energy and exergy efficiency before and after optimization

machine as shown in fig. 12. It represents a comparison of various parameters before and after optimization. Steam consumption reduced from 3.55 to 2.74 ton per ton of paper produced. Condensate recovery jumped from 40 % to 65%. These parameters corresponded to an increase in energy and exergy efficiency from 46% to 68% and 29% to 43%, respectively.

Conclusions

Fault tree analysis approach was used for the first time for energy optimization. It yielded fruitful results not only in identification of key problems but also in the development of corrective actions. With help of this approach steam consumption improved from 2.74 to 3.55. Condensate recovery, energy, and exergy efficiencies enhanced from 40 to 65%, 46 to 68%, and 29 to 43%, respectively.

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