Eenrgy conservation approaches in a paper mill with special references to the evaporator plant

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SUMMARY

The pulp and paper industry is an energy intensive industry consuming total purchased energy about 7.62 GCal to 13.25 GCal tonne of paper, ranking in heavy industries after steel and petrochemical industries. The availability of energy, the mounting pressure for preserving environment and ecology and rising cost of production is a matter of concern to the pulp and paper industry. The need for improving the productivity and efficiency at all stages of the manufacturing process is the prime necessity today. The major problems faced by the pulp and paper industry are lack of sustained supply of raw-material, failure of infrastructure (like supply of coal, power etc.); concern for energy, environment and ecology; high capital intensive nature, fast technological changes; rise in paper quality and reduction in the margin of the profit.

In this paper, general strategy of the energy conservation in the pulp and paper mills have been discussed section wise and Evaporator Plant has been analysed in detail. The parameters like steam economy and steam consumption have been calculated on the basis of existing data. Three alternative schemes with minor modifications have been attempted and the corresponding energy consuption and steam economy figures have been calculated which are found to be better than the existing practice. It is possible that without major investment and providing minor modifications in the existing plant configuration, the steam consumption in terms of steam econcmy can be improved leading to the cost reduction. This needs a close look by the Industry.

The paper industry is known to be an energy intensive industry consuming total purchased energy from 7.62 GCal to 13.25 GCal per tonne of paper, ranking in heavy industries after steel and petrochemicals industries. The impact of the energy prices and its supply position has been very severe on the economics of the paper industry. There is a need to think seriously bv seeking the ways and means to meet the energy needs and reduce the demand to achieve and sustain the industry. The cost of energy input has gone very high i e. purchased power rate which was 19 paise per kwh in 1974 has shot up 90 paise in Gujrat State in 1983 and fuel oil which was available at Rs. 175/= per tonne in 1967 has sky rocketed to Rs. 2900/= per tonne in 1983. Similarly the coal prices have increased from Rs. 90/= in 1967 to Rs. 415 in 1983 on per tonne basis. In the cost of production of paper today 15—20% of the total cost is due to the energy. Therefore, it is imperative that energy conservation aspects has to be taken into consideration and implemented effectively to reduce the energy usage.

ENERGY CONSUMPTION POSITION :

In a recent study (4), the production and energy related data of six large Indian Paper Mills has been summarised. Table No. 1 shows such data.

As can be seen, there is a wide variation in energy consumption and its cost among the mills. i.e. from 7.62 to 13.25 GCal per tonne of paper and Rs. 343/= to Rs. 1182/= per tonne of paper (1983). The steam consumption varies from 10 5 to 17.4 tonne of paper and the power consumption varies from 1305 1949 kwh. The amount of on site power generation is 23.4% to 100% the total power used.

The table No. 2 shows the comparision of break up of energy utilisation of a typical Indian integrated paper mill v/s. a Swedish integrated bleach paper mill. This table indicates that Swedish mill purchases on an average 40% of total energy requirement to produce one tonne of paper as against 70% an average figure for Indian mills. This is due to the fact that paper mills in abroad are less dependent on purchased fossil fuels and power as they use more of the locally available by-product energy resources with attendant high efficiency.

The table No. 3 gives the comparative specific energy con-

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TABLE NO. 1
COMPARATIVE ENERGY COSTS AND CONSUMPTIONS IN LARGE MILLS IN INDIA (4)

Mill	1.	2.	3.	4.	5.	6.
1. Raw Meterial, % Bamboo/Wood/Pulp.	75/25/-	100/- /-	40/60/-	51/44/5	70/30/-	90/-10
2. Installed/Production capacity, TPA, in 1000	85/61.3	Paper 33/ 12.694 Pulp 39/2.295	75/66.832	67.5/51.283	52.8/53.701	46.2/36.931
3. Purchased energy.						
(a) Coal/oil TPA, in 1000.	125.328/ 0.2.	30.572/ 2.287	129.903/ 1 465	89.447/ 2.923	77.438/ 11.068	46.034/1.68
(b) Power, kwh, in 1000.	Nil	19372	83810	102565	49285	25970
Self Generation, kwh, in 1C00.	931996	9327	33215	31283	35389	22380
% of self total tower.	100	32.5	28.5	23.4	41.8	46.3
Specific figures per tonne of paper.						
Energy pu chased G Cal.	10.71	13.25	10 03	10.13	10.16	7.62
Energy cost, Rs.	343	1182	898	1090	1144	869
Power, kwh.	Nil	1296	1213	1339	917	699
Self generation, kwh.	1520	649	497	610	659	606
Total Powe, kwh	1520	1945	1710	1949	1576	1305
Steam, Tonnes.	16.9	17.4	11.6	13.0	10.5	11.6

TABLE No. 2
COMPARISION OF BREAK UP OF ENERGY UTILIZATION OF A TYPICAL INDIAN AND SWEDISH INTEGRATED KAFT BLEACHED PAPER MILL (1)

Description	Indian Mill 1980-81	Swedish Mill 1979
1. Purchased Energy (G Cal)		
(i) Fuel	9.37	3.53
(ii) Power	0 79	0.76
Total	10.16	4.29
II. Fuel Sources (G Cal)		
(i) Purchased fuel	9.37	3,53
(ii) Internal Fuel (black liquor, bark etc.)	4.58	4.65
Total	13.95	8.18
III. Fuel source utilisation G Cal)		
(i) Steam Cycle & processes.	11 47	7.38
(ii) Back Pressure Power.	2 48	0.80
Total	13 95	8.18
IV. Electricity :—		
(i) Purchased Power	918	902
(ii) Back Pressure power.	658	787
Total	1576	1689
Back pressure power generation efficiency, %	22.8	85

sumption in three different integrated Indian paper mills. Analysing the power and steam consumption in different sections, it is clear that major consumer of the steam are pulp mill, evaporators and paper machine and while major consumer of the power are the chipping section and paper machine. The chipping has vast variation in specific power consumption from 74. to 120 kwh. The lower consumption indicates the use of high capacity and more efficient chippers.

In case of small paper mills, having no chemical recovery and entirely depend on purchased energy. Primary fuel based co-generation of power is also not practised. However the specific energy consumption is lower because of the nature of the raw-material used. The specific cost of energy varies from Rs. 351/— to Rs. 1129 per tonne of paper (1983).

STEPS TO IMPROVE ENERGY EFFICIENCY :

The major areas where the paper industry has to concent-

TABLE No. 3

SPECIFIC ENERGY CONSUMPTION IN INTEGRATED KRAFT PAPER MILLS (4)

Section	Per Tonne of Product		
Mill No.	1.	2.	3.
I. Steam, in tonnes.			
Pulp Mill	3.9	2.7	2.69
Evaporators.	4.0	2.5	2.18
Soda Recovery.	00.5	1.1	1.05
Bleach Plant.	0.4	0.4	0.20
Paper Machine.	4.0	3.0	3.64
Deaerator	1.2	0.8	0.97
	14.0	10.5	10.73
Energy, G Cal	9.184	6.888	7.039
II. Power, in kwh Chippers	120	80	74
Digesters	60	50	37
Washing and Screening.	150	130	120
Bleach Plant	90	130	94
Soda Recovery	180	120	115
Stock Preparation	280	130	276
Paper Machine	470	530	366
Utilities and others.	250	210	419
Total Power	1600	1400	1501
Power, G Cal	1.376	1.204	1.291
III- Total Energy (I + II) G Cal.	10.560	8.092	8.330
IV- %, Steam to Power	87/13	85/15	84.5/15.5

rate to raise its status in the energy efficiency heirarchy among the various industrial sectors are :

Steam and Power generation, Plant Hydraulic System.

By-Product energy utilisation.

Water Conservation and Energy Conservation in processes.

Steam and Power Generation :

It is the primary area of concentration for conservation measures as all the fuels (about 95%) are consumed to generate the steams. The steam generation parameters of fossil fuel fired and chemical recovery boilers range from 18 kg/cm², 310°C and 10 tph to 60 kg/cm², 440°C and 85 tph.

Small mills invariably generate saturated steam at 10 kg/cm² and the capacities varies from 4 to 10 tph. The boiler have poor thermal efficiency i.e. as low as 58% as against a possible value of 70–75% which indicates the scope for improvement. The main factors which are responsible for poor steam generation efficiency, are old boilers with poor heat recovery design, deteriorating coal quality, inadequate coal handling, absence of operational skill and lack of proper instrumentation and control to take care of fluctuating loads.

Co-generation potentiality of the paper industry is highest among the energy intensive industries. The wide variation of by-product power generation of the large paper mills varies from 23% to 100% or 400 to 1500 kwh per tonne of paper indicates the possibility of exploiting the optimum co-generation potential. Therefore the following measures can be taken which do not have any major investment decisions :

(1) Power coal handling,

(2) Improvement in the skill of the operating personnel,

(3) Adequate instrumentation for control and monitoring,

(4) Provision of the heat trap devices like economisers and preheaters, and

(5) Efficient and load management.

Plant Hydraulic Systems :

About 40 to 50% of the paper mill power consumption is used for pumping the fluids from one point to another. Very high potential for power savings with attractive return on the investment is hidden in pumping systems that can be seen, i.e. a Finish paper mill, having 900 kwh. Specific power consumption as compared to Indian Large Paper Mill is around 1500 kwh per tonne of paper. It is also found that about 20%, as the conservation potential exists in the pumping systems in our mills, which have the possibility of saving about 200 kwh per tonne of paper. This saving does not require the big investment, sophisticated software and hardware but better understanding of the pumping systems, optimisation and redesign of hydraulic systems, if required, changing/interchanging of pumps and impellers to more efficient configurations and selection and matching of pumps and drives to near optimum conditions.

By-Product Energy Utilisation :

Paper industry all over the world is working towards "Zero purchased energy concept" while in some Swedish mill on an average purchased energy constitute only 40% of their requirement as against of 70% for large Indian paper mills. This indicates the need for greater internal power generation. The following steps can be thought from the point of view of increasing internal generation of power :

(1) Implementing the concept of "Whole Tree Utilization",

(2) Utilise the residues of harvesting and cutting operations of lumber in the forests, bark and dust generated in the mill.

(3) Burning of mill sludge as supplementry energy in the incinerators.

Water Conservation :

Paper industry is a major consumer of water and in specific water consumption in Indian mills varies from 250M³ to 450 M³ per tonne of paper as compared to the less than 100 M³ per tonne of the paper in the American Paper Mill. This provides a lot of scope to reduce the fresh water requirement in Indian and recycle the water. This will not only cut down the process heat requirement but also result in lowering power consumption for pumping.

The measures which can be taken are maximum recycling of water, avoid the unnecessary running and overflows, optimisation of the process like the chlorination stage in bleaching and reutilization of the contaminated condensate at the appropriate stages.

Energy conservation in the processes :

The demand and effective utilization of the heat and electrical energy largely depends on the basic design and choice of the process equipments. Paper industry can achieve the energy savings in the processes by initiating time bound action plans in two majors heads namely house keeping measures and capital improvements. In house keeping measures efforts are needed to improve the plant operation and maintenance practices which can achieve rapid results without much any significant capital expenditure. Capital improvements might include retrofitting heat trap devices, recycling and reuse of energy and materials, replacement of multiple, old small inefficient pieces of the equipments and better instrumentation and control systems. These measures can be classified as short, medium and long term based on the cost benefits and company investment criteria. Some of the important steps, in each section of the paper industry which can provide the energy conservation are discussed below :

PULP MILL :

1. Recovery of heat energy from digester blow gases as maximum as possible as 0.6—0.7 tonne of vapour/tonne of pulp are flashed during blowing.
2. Proper lagging of the digester avoid the heat loss.
3. Higher capacity of the batch digester and proper circulation of liquor.
4. Use indirect heating to reduce evaporation load and better pulp yield.
5. Use the amino methylene phosphate to reduce the scaling.
6. Maintain low bath ratio for proper cooking and blowing.
7. Avoid blowing of chips with compressed air. Use belt conveying system.
8. Use computer control of the digester for effective maintence of the operating conditions.
9. Use turpentine decanter at highest possible temperature
10. Maximum advantage of barometric leg to reduce power load on vacuum pumps.
11. Use diffusion washing which requires less power.
12. Minimise the pressure drop in screening to reducc the power consumption.
13. Maintain highest feasible consistency in bleaching operations.
14. Maintain Low stock temperature.
15. Use counter current washing.
16. Use continuous digester in place of batch digester, which provide 40-50% less steam and give 2% higher concentration of black liquor.
17. Displacement heating and cold blowing the batch digester with compressed air promises 75% steam saving and 2% rise in black liquor concentration.
18. Replacement of conventional sequence CEH or CE-

HH bleaching by O - P - H to have better brightness and less effluent load. The O_2 manufacture require half of the energy as compared to chlorine manufacture.

19. Use of anthroquinone pulping to reduce sulphidity and increase yield.

EVAPORATOR PLANT :

1. Reduce the evaporator tube fouling with fibres using the strainers.
2. Proper control of black liquor boiling alongwith the steam flow.
3. Maintain the perfect vacuum in the system.
4. Practice soap recovery to reduce fouling.
5. Optimisation of cleaning time for each effect.
6. Use low temperature cooling water in condensers.
7. Utilise the flash vapours as maximum as possible.
8. Provide the proper insulation.
9. Provide the accurate flowmeters for steam transmission.
10. Avoid the accumulation of the condensate in the avaporator body.
11. Maintain the proper concentration of black liquor to the evaporation plant as drop in black liquor concentration from 16% to 10% T.S., the steam consumption in evaporator is almost double to achieve the same output.
12. Application of falling film evaporator with plate type heating surfaces permits evaporation of the liquor at higher solids concentration, reduces water or chemical boiling for scale removal and give better control on exit black liquor concentration.
13. Replacement of mild steel tubes with stainless steel tubes.

RECOVERY BOILER :

1. Proper control of black liquor solids, excess air and salt cake make up as :
   (i) One percent drop in black liquor concentration reduces 2.67% steam generation. Lower black liquor solids to furnace upsets the furnace bed and lead to auxiliary fuel firing.
   (ii) Drop in excess air from 25% to 18% reduces the load on I.D. fan by 20% and increases steam generation by 0.2 to 0.3%.
   (iii) Excess salt cake feeding will reduce steam generation.
2. Proper control of temperature of black liquor and preheated air.
3. Regulate the soot blowing operation by proper spacing.
4. Generate steam at highest possible temperature and pressure.
5. Extract the steam at lowest possible pressures from the turbine and use non-condensing type turbine.
6. Energy recovery through the flue gases.
7. On line control of flue gas analysis.
8. Maintenance of the proper level of water in boiler drum to ensure the continuous supply of the steam to the turbine.
9. Proper distribution of steam through header.
10. Proper maintenance of steam traps.
11. Proper belting and shafting for motors.
12. Proper insulation to pipe line, valves and joints.
13. Add the appropriate quantity of steam in direct heating.
14. Proper spraying technique of black liquor.
15. Avoid the formation of CO and H_2S in the furnace.
16. Maintain the proper distribution of the air through airports.
17. Avoid the supply of low temperature water to the economiser.
18. Use of modern and efficient alternatives like molten salt gasification of black liquor, Hydro pyrolysis of black liquor, as alternative to Tomilson furnace.
19. Proper operation of the desuper heater.
20. Keep the sufficient passage for easy flow of flue gases.
21. Use the vapours of the smelt Dissolver for the recovery of the heat.
22. Reduce the fluctuation in process steam and power requirements.

CAUSTICIZING AND LIME RECOVERY :-

1. Maintain the higher white liquor concentration and temperature which reduces the steam demand in digester and evaporator and better performance in brown stock washing.
2. Use optimum number of mud washing stages.
3. Avoid the accumulation of mud in clarifiers and mud washer at the bottom.
4. Maintenance of the proper vacuum in vacuum drum filters to reduce the moisture-content in sludge.
5. Use dry lime sludge to have effective utilization or en-

ergy in the lime kiln.

6. Proper maintenance of the operating conditions to have better quality of Lime and optimum supply of fuel.

Stock Preparation and Paper Machine :—

1. Selection of the proper type of the refiner for different type pulps and their sequences play an important role in energy conservation approaches.
2. Application of computer control provides optimum use of refining energy.
3. Refine the stocks at high pH which leads to less frictional resistance.
4. Provide properly designed save alls.
5. Provide variable speed fan pumps.
6. Utilize the flash steam in dryers itself as maximum as possible.
7. Carry out on line computer control of the paper properties.
8. Accurate control of flow of seal water and temperature.
9. Increase the dryness of paper web after the press which leads to increase in production and saving of steam i.e. 1% increase in dryness gives 4% saving in steam.
10. Refine at higher refiner housing pressure.
11. Improve press section.

4. CASE STUDY OF THE EVAPORATOR PLANT :

To analyse the thermal performance of the evaporator plant, an evaporator plant having five efforts of an integrated paper mill is selected. The operating parameters and properties of liquor and steam, used in the calculation are shown in Table No. 4.

TABLE NO. 4

OPERATING PARAMETERS AND PROPERTIES OF BLACK LIQUOR AND STEAM

Black Liquor	Steam
Feed rate=66770 kg/hr. Inlet Feed Concentration =23% T.S.	Feed rate=10910 kg/hr. Pressure (L.P.)=2 25 kgf/cm² (g)
Outlet feed concentration =48% TS	Temperature=136°C.
Feed Temp.=95.°C.	Vacuum in the last effect =400.8 mm Hg.
Average Specific heat, kcal/kg°C. =0.82	Cost=Rs. 100 per tonne.
(in Temp range, 71°—124°C and Concentration range, 23—48% TS)	Operating days=330 in a year

The existing system has the mixed feeding method and weak liquor is supplied to the third effect which followed to fourth, fifth, second and first effect, shown in Fig. 3. The table No. 5 shows the exsiting feeding rate, temperature, pressure details and also give the calculation of the steam economy which comes out to be 3.187 by solving the set of simultaneous equations given in appendix-1. Taking the average specific heat of the black liquor for the given temperature range. The above value of steam economy is low as compared to 3.750 value taking normal value of 0.75 for each effect. Then, the following alternatives have been analysed to improve the steam economy :

ALTERNATIVE I :

Change in feeding method i.e. instead of feeding weak black liquor in third effect, the liquor is fed in fourth effect.

ALTERNATIVE II :

Addition of flash vessels in the existing systems.

ALTERNATIVE III :

Addition of flash vessels in the proposed feeding sequence in Alternative-I.

Steam economy calculations have been carried out for the above three alternatives by using the material and energy balance equations given in appendices I and II and results are shown in table No. 6 and 7. The calculated steam economy values clearly indicate that in all the three alternatives, it is improved from 3.187. The alternative III gives the maximum steam economy as 3.771.

The above alternatives will require some investment but looking into the annual steam cost, which are calculated and given in table No. 8, it is found

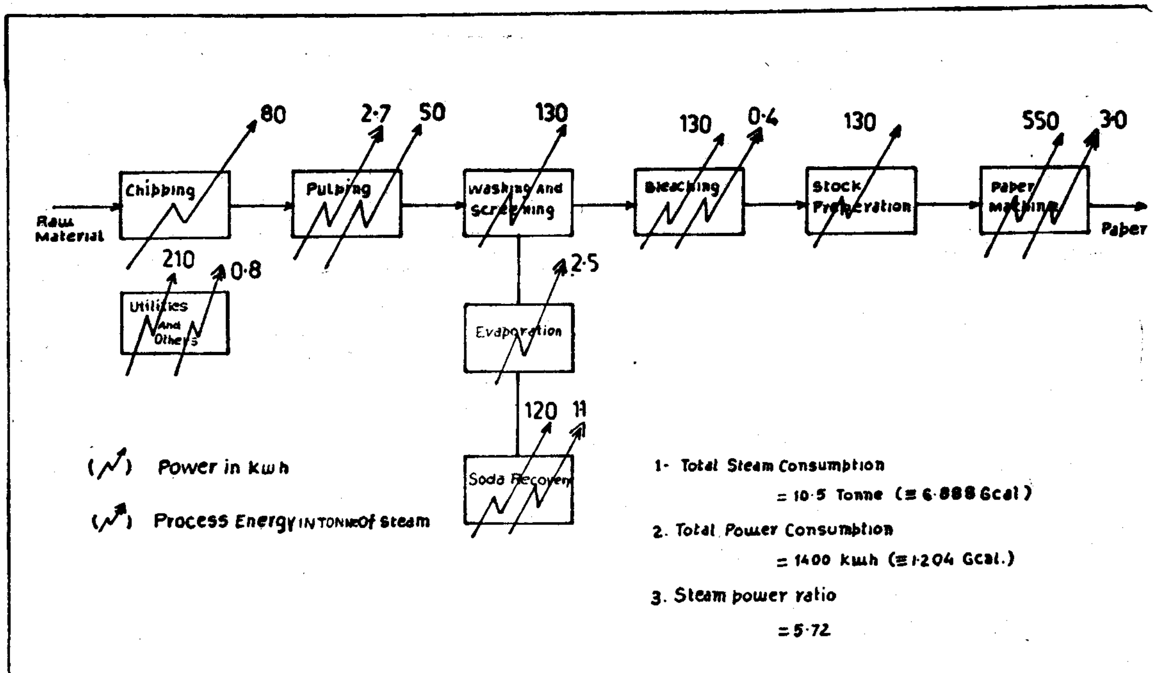

Fig. 1 SPECIFIC ENERGY CONSUMPTION IN A TYPICAL INTEGRATED KRAFT PAPER MILL
BASIS :—One Tonne Of Paper

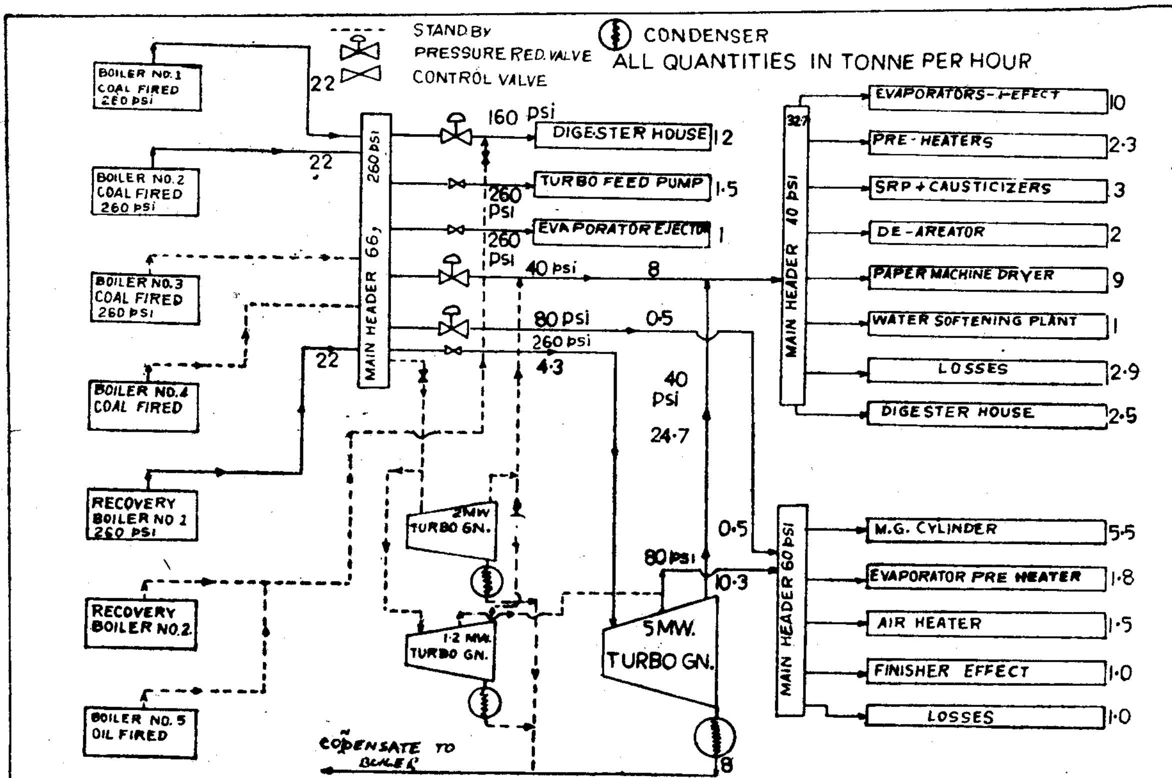

Fig. 2

STEAM GENERATION AND ITS DISTRIBUTION IN AN INTEGRATED PAPER MILLS OF 100 TPD PRODUCTION

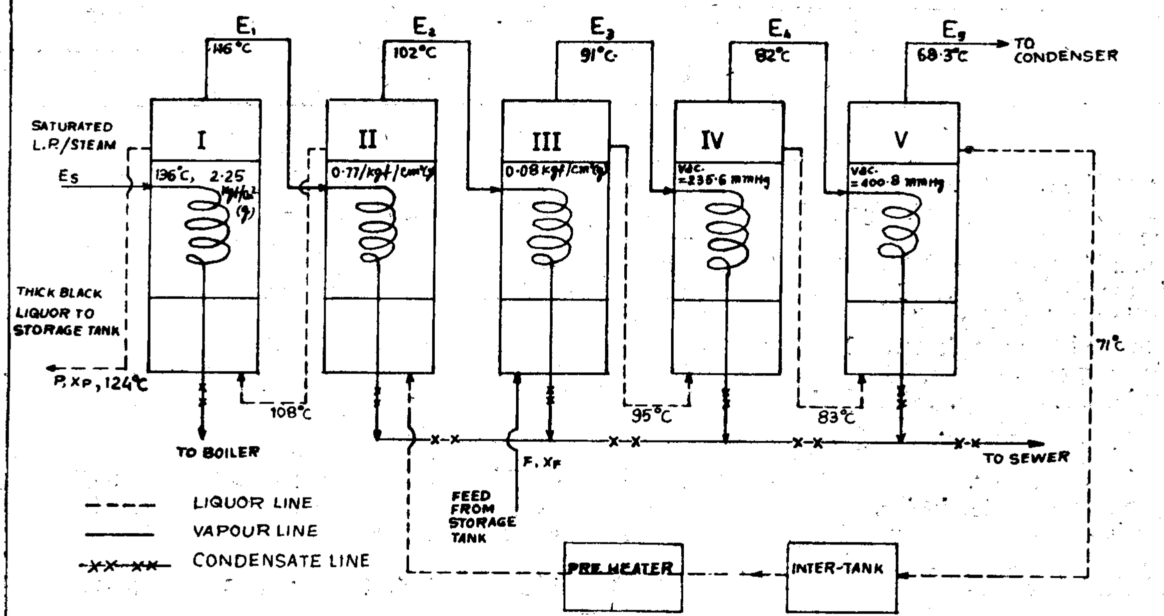

Fig 3 EXISTING FEED SEQUENCE IN EVAPORATOR PLANT

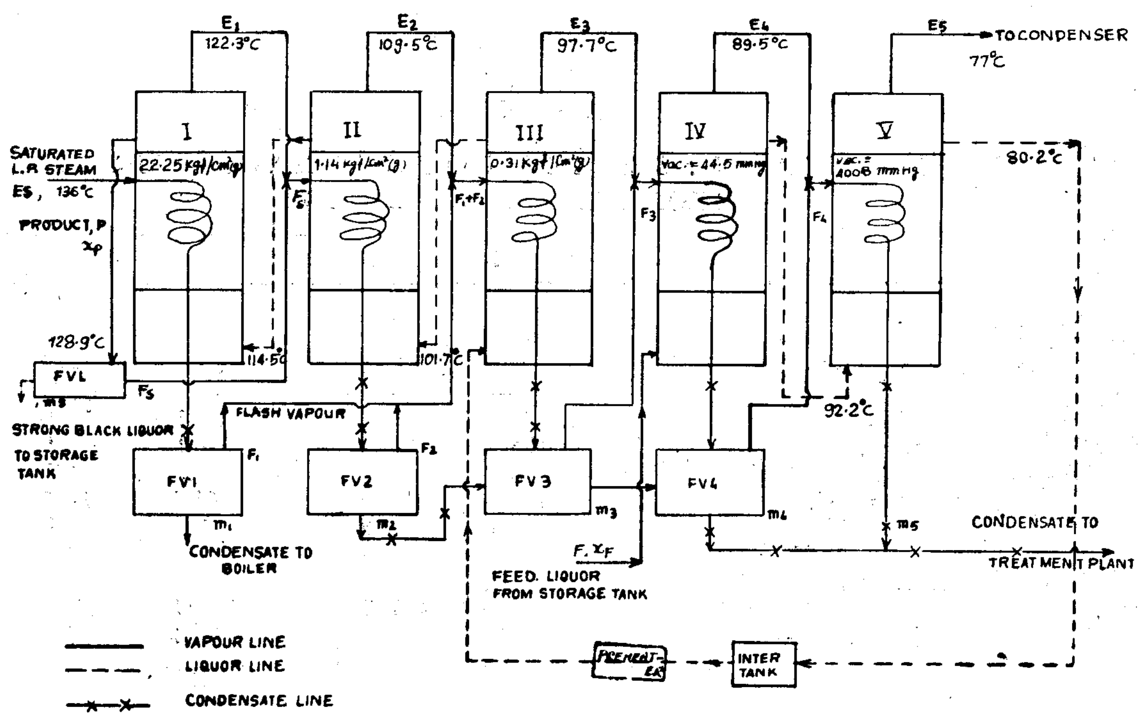

Fig.4. EXISTING FEEDING SEQUENCE WITH FLASH VESSELS FOR CONCENTRATED BLACK LIQUOR AND CONDENSATES (Alternative III)

TABLE NO.—5

STEAM ECONOMY CALCULATIONS FOR EXISTING FEEDING METHOD

	I	II	III	IV	V	Finisher
Steam Feed, kg/hr.	10910					
Steam pressure, kgf/cm² (g)	2.25	0.77	0.08	—	—	
Vacuum, mmHg	—	—	—	235.6	400.8	
Steam Temperature, °C	136	116	102	91	82	
Liquor Temperature, °C	124	108	95	85	71	
Boiling Point Rise, °C	8	6	4	3	2.7	
Saturated Vapour Temp., °C	116	102	91	82	68.3	
Working temp. Drop, °C	12	8	7	6	11	
Feed concentration, Inlet %TS	40	35	23	26.2	29.3	
Feed Concentration, outlet % TS	48	40	26.2	29.3	35	
Feed Rate, kg/hr.	38393	43877	66770	58615	524.3	31994
Evaporation Rate, kg/hr.	6399	5484	8155	6202	8536	
Heating Surface Area, m²	366.6	411.5	366.6	366.6	366.6	
Overall Heat Transfer Coeff. X kCal/m²hr. °C	1283.8	1029.2	1151.4	1637.3	970.3	

Steam Economy=3.187.

TABLE NO.—6

ALTERNATIVE—I : STEAM ECONOMY CALCULATIONS FOR PROPOSED FEEDING METHOD

	Finisher	I	II	III	IV	V
Steam Feed, kg/hr.		9679				
Steam Pressure, kgf/cm² (g)		2.25	1.14	0.31	—	—
Vacuum, mm Hg		—	—	—	44.5	400.5
Steam Temperature, °C.		136	122.3	109.5	97.7	89.5
Liquor Temperature, °C.		128.9	114.5	101.7	92.2	80.2
Boiling Point Rise, °C.		6.6	5.0	4.0	2.7	3.2
Saturated vapour Temp., °C.		122.3	109.5	97.7	89.5	77
Working Temp. Drop., °C.		7.1	7.8	7.8	5.5	9.3
Inlet Feed concentration, %TS		—	—	—	23	—
Outlet Feed concentration, % TS		48				
Feed Rate, kg/hr	31994	39699	47107	54291	66770	60083
Evaporation Rate, kg/hr.	—	7705	7408	7184	6687	5792

Steam Economy =3.593.

TABLE No. 7

STEAM ECONOMY CALCULATIONS FOR EXISTING AND PROPOSED FEEDING METHODS WHEO FLASH VESSELS ARE ADDED

	Extra xapours Generated, kg/hr.	Evaporation Rate kg/hr.	Steam feed rate kg/hr.	Steam Economy
Alternative—II				
When flash vessels are	$F_5=255.4$	$E_1'=6654.4$		
added in the existing	$F_1=700.0$	$E_2'=6359.2$	10910	3.347
feeding methods.	$F_2=175.2$	$E_3'=8417.8$		
	$F_3=262.8$	$E_4'=6544.8$		
	$F_4=342.8$	$E_5'=8536.0$		
Alternative—III				
When flash vessels are	$F_6=248.3$	$E_1'=7953.3$		
added in the proposed	$F_1=493.4$	$E_2'=8092.2$		
feeding methods.	$E_2=109.8$	$E_3'=7532.9$	9679	3.771
	$F_3=348.9$	$E_4'=7133.4$		
	$F_4=346.4$	$E_5'=5792.0$		

TABLE No. 8

COMPARISION OF THE EXISTING AND PROPOSED ALTERNATIVES

Description	Steam Economy	Steam Consumption kg/hr.	Steam saving w.r.t. existing feeding, kg/hr.	Annual saving, Rs. in lakhs.
1. Existing Feeding sequence.	3.187	10910	—	—
2. Alternative-I	3.593	9679	1231	9.75
3. Alternative-II	3.347	10910	547.7	4.34
4. Alternative-III	3.771	9679	1710.5	13.55

that about Rs. 13.55 lacs/annum can be saved in alternative III, which is quite high. Therefore, the above alternatives require a close look by the industry.

CONCLUSION :

The following conclusion can be drawn on the above study :

(1) Improvement in the steam Economy of the existing evaporator plant from 3.187 to 3.771 in alternative-III.

(2) The alternative-III will require some investment but the annual saving of Rs. 13.55 lacs per year indicates that the above alternative will be worthwhile to implement in the industry.

(3) For the calculations, the heat-transfer coeffieient values has been taken on the basis of the existing conditions, which will definitely improve in the new temperatures and pressure distributions.

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7. NOMENCLATURE :

C_{p1}—Avg. Specific heat of black liquor, kCal/kg°C.

$E_{1,2,3,4,5}$—Vapour feed rate, from I to IV effect, Kg/hr.

E_s—Steam flow rate, kg/h.r

F—Weak black liquor feed rate, kg/hour.

F_s—Flash vapour from strong black liquor, kg/hr.

$F_{1,2,3,4}$.—Flash vapours from flash vessels 1, 2, 3 & 4 kg/hr.

h_{1s}—Liquor heat content kCal/kg.

h_{vs}—Flash vapour from FVL, kg/hr.

$h_{v1,2,3,4}$—Flash vapour from flash vessels 1 to 4, kg/hr.

m_s—Strong B/L from flash vessel FVL, kg/hr.

$m_{1,2,3,4}$—Condensate flow from flash vessel FV_1 to FV_4, kg/hr.

S—Steam Economy, kg of H_2O evaporator per kg of steam supplied.

t_{1f}—Weak black liquor feed temperature, °C.

t $l_{1,2,3,4,5}$—black liquor outlet temperature from I to V effect, °C.

λ_s—Latent heat of steam, kCal/kg.

$\lambda_{1,2,3,4,5}$—Latent heat of vapour from I to V effect, kCal/kg.

X_f—Weight fraction of solids in feed, F

X_p—Weight fraction of solids in product, P.

APPENDIX NO.—1

MATERIAL AND ENERGY BALANCE EQUATIONS FOR THE EXISTING SEQUENCE SHOWN IN FIG. 3 OVERALL MATERIAL BALANCE ACROSS THE WHOLE UNIT

Overall Material Balance across the whole unit

$$F = P + \sum_{i=1}^{5} Ei \qquad \ldots\ldots (1)$$

Dry solids balance,

$$x_F \cdot F = x_p . P \qquad \ldots\ldots (2)$$

Energy Balance across,

I Effect :

$$E_s\lambda_s = E_1\lambda_1 + (F - \sum_{i=2}^{5} Ei)\, C_{p1}\, (tl_1 - tl_2) \qquad \ldots\ldots (3)$$

II Effect :

$$E_1\lambda_1 = E_2\lambda_2 + (F - \sum_{i=3}^{5} Ei)\, C_p l_2\, (tl_2 - tl_3) \qquad \ldots\ldots (4)$$

III Fffect :

$$E_2\lambda_2 = E_3\lambda_3 + (F - \sum_{i=4}^{5} Ei)\, C_p l_2\, (tl_3 - tl_4) \qquad \ldots\ldots (5)$$

IV Effect :

$$E_3\lambda_3 = E_4\lambda_4 + F\, C_{pl_4}\, (tl_4 - tl_F) \qquad \ldots\ldots (6)$$

V Effect :

$$E_4\lambda_4 = E_5\lambda_5 + (F - E_4)\, C_{pl5}\, (tl_5 - tl_4) \qquad \ldots\ldots (7)$$

Steam Economy :

$$S = \frac{\sum_{i=1}^{5} Ei}{E_s} \qquad \ldots\ldots (8)$$

Similar equations can be developed for the feed sequence, proposed in alternative—I

(i.e. WBL ⟶ IV ⟶ V ⟶ III ⟶ II ⟶ I)

APPENDIX—2

MATERIAL AND ENERGY BALANCE EQUATIONS FOR THE FLASH VESSELS PROPOSED IN EXISTING FEEDING SEQUENCE

Strong Black Liquor Flash vessel (FVL)

Material Balance

$$(1-x_p).\ P = m_s + F_s \qquad \ldots\ldots \quad (9)$$

Energy Balance :

$$hl_p\,(1-x_p)\cdot P = m_s.hl_s + F_s.h_{vs} \qquad \ldots\ldots \quad (10)$$

Flash vessel (FV_1)

$$E_s = m_1 + F_1 \qquad \ldots\ldots \quad (11)$$

$$Hl_sE_s = hl_1m_1 + F_1h_{v1} \qquad \ldots\ldots \quad (12)$$

Flash vessel (FV_2)

$$E_1 + F_s = m_2 + F_2 \qquad \ldots\ldots \quad (13)$$

$$hl_1\,(E_1 + F_s) = hl_2m_2 + h_{v2}.F_2 \qquad \ldots\ldots \quad (14)$$

Flash vessel (FV_3)

$$E_2 + F_1 + F_2\ m_3 + F_3 \qquad \ldots\ldots \quad (15)$$

$$hl_2\,(E_2 + F_1 + F_2) = hl_3m_3 \times h_{v3}.F_3 \qquad \ldots\ldots \quad (16)$$

(Flash vessel FV_4)

$$(E_3 + F_3) = m_4 + F_4 \qquad \ldots\ldots \quad (17)$$

$$hl_3\,(E_3 + F_3) = hl_4\,m_4 + h_{v4}.F_4 \qquad \ldots\ldots \quad (18)$$

Similar equations can be developed for the new proposed feeding method with flash vessels (Alternative-III).