Thermal Energy Analysis in a Sugar Mill

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ABSTRACT

Energy consumption by a steam generation plant in a sugar mill, located in Khon Kaen province, Thailand, is investigated. The capacity of the bagasse fired boiler is 80 ton/hour. Energy and availability analyses are used to identify the locations, types and magnitudes of the losses. The results show that the first, and second law efficiencies for the best case of the boiler are 59.6% and 21.3% and for the worst case are 57.9% and 20.3%, respectively.

The feasibility of drying bagasse with flue gas is also studied. Assuming the heat exchanger effectiveness to be 0.7, the maximum permissible costs of the dryer at an interest rate of 15% per annum with a pay back period of two years is 1,316,000 baht, and with a pay back period of five years is 2,713,000 baht. The maximum possible saving of bagasse by means of drying is expected to be 976,000 baht per boiler per milling season, assuming the price of bagasse to be 250 baht per ton.

During the study, about 140% of excess air was charged into the boiler. It seems possible to reduce this, thus enabling a further saving of bagasse.

INTRODUCTION

Sugar production from cane is one of the major agro-industries in Thailand; there are now 45 sugar mills in the country. In 1984, the total production of sugar was about 2.2 million tons from which 1.2 million tons were exported at a value of 5,010 million baht [1].

The sugar mill under investigation in this paper is located at Khon Kaen in the northeastern part of Thailand. The factory was built in 1976 at a cost of about 600 million baht. The factory operates 4 bagasse-fired boilers which produce superheated steam for power generation and process heat. The milling period lasts about 3-4 month per year with the cane consumption rate of 10,000 tons per day [2].

A flow diagram of the plant is shown in Fig. 1. In addition to three turbogenerators for electric generation, there are five milling turbines and one unigator turbine run by superheated steam from the boilers. Exhaust steam from the turbines is used in the downstream process. Generated electricity is consumed not only in the sugar mill, but also in a bagasse board factory which is located next door to the mill.

BOILER ANALYSIS

Boiler no.4 was selected for the case study. The boiler was designed to produce 80 tons/hour of steam at 26 bars. During the milling season, the four boilers operate 24 hours every day. A flow diagram of the boiler is given in Fig. 2.

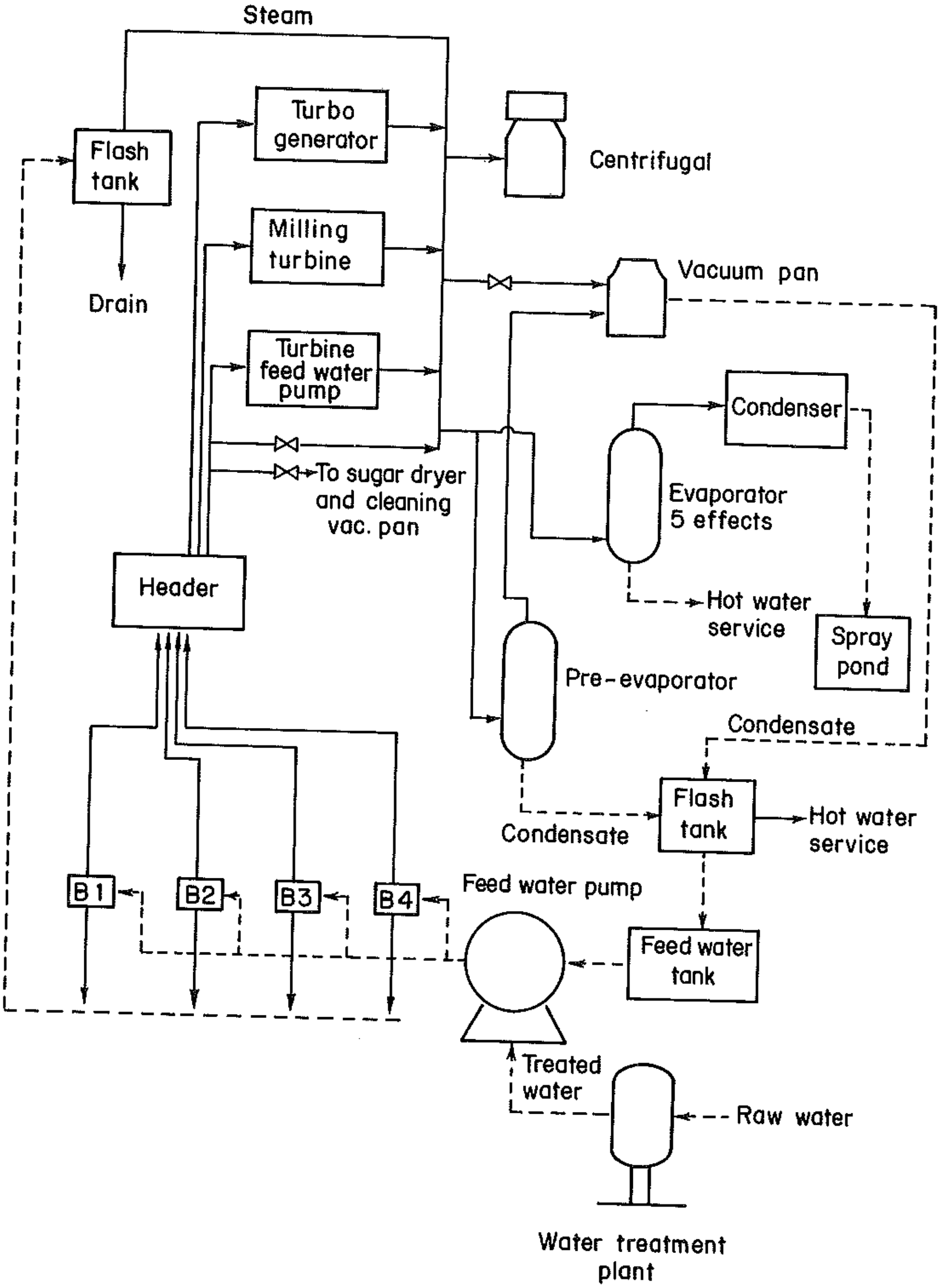

Fig. 1. Schematic diagram of steam flow.

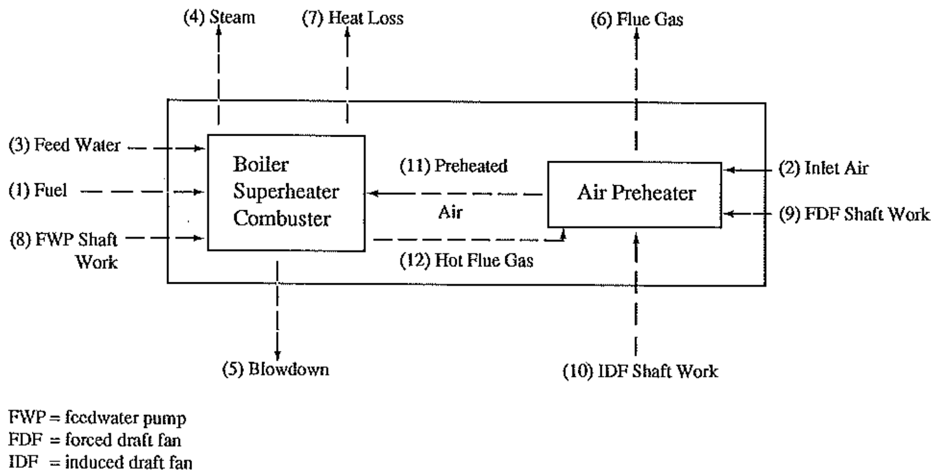

Fig. 2. Boiler unit and its boundary.

Energy Analysis

In the energy analysis of the boiler, the following flow streams are involved.

Fuel

Bagasse was used as fuel for the boiler. From an ultimate analysis, bagasse, as fired, contained 22.5% C, 2.96% H, 21.31% O, 0.07% S, 0.13% N, 2.08% ash and 50.95% moisture. Bagasse, as fired, had a higher heating value, HV of 8819 kJ/kg. The feed rated of m_f was about 30,000 kg/h.

Air and flue gas

Before entering the combustion chamber, air was preheated from ambient temperature, t_0 to a temperature, t_2 of about 240°C. The flue gas left the preheater at a temperature, t_6 of about 197°C.

Enthalpy loss with the dry flue gas

$$= m_a C_{pa} (t_6 - t_0)$$

where m_a = mass flow rate of dry flue gas, and

C_{pa} = specific heat of air at constant pressure.

Feed water and steam

Feed water, a mixture of condensate and make-up water, was pumped from the condensate tank at a temperature, t_3. Superheated steam was generated at a temperature, t_4 of about 380°C, 22 bars. The average steam flow rate, m_s was 54,670 kg/h.

Enthalpy increase in superheated steam

$$= m_s (h_4 - h_3)$$

Blow-down

To prevent the build up of solids, continuous blow down of saturated steam was carried out at a rate, m_b of 3000 kg/h.

Enthalpy lost in the blow down

$$= m_b (h_{sat} - h_3)$$

Moisture in fuel

Bagasse, as fired contained more than 50% moisture.

Enthalpy lost due to moisture in the bagasse

$$= m_m (h_6 - h_0)$$

where m_m = mass rate of moisture in fuel, and
h_0, h_6 = specific enthalpies of moisture as fired and at the flue gas temperature, t_6.

Moisture from H in bagasse

Hydrogen in bagasse burns and yields additional moisture in the flue gas.

Energy loss due to H in bagasse

$$= 9H(h_{fg} + h_6 - h_0)\, m_f$$

where H = mass of H in 1 kg of bagasse, and
h_{fg} = latent heat of vaporization of water
m_f = mass rate of bagasse.

From the above energy and mass flows, the energy balance equation for the boiler can be written as:

$$m_f HV + W_e = Q_s + m_a C_{pa} (t_6 - t_0) + m_s (h_4 - h_3) + m_b (h_{sat} - h_3)$$
$$+ m_m (h_6 - h_0) + 9H (h_{fg} + h_6 - h_0)\, m_f \quad (1)$$

where W_e = electrical power for feedpump, air blower and bagasse feeder,
Q_s = heat lost from the boiler surface and in practice measured by a heat flux meter.

The first law efficiency, η

$$= \frac{m_s (h_4 - h_3)}{m_f HV + W_e}$$

Results of the energy analysis of Boiler no.4 at 9, 10 and 11 a.m. are shown in Table 1.

Table 1. Energy balance of boiler no. 4.

Energy flow	Best case		Worst case	
	kJ/kg of fuel	%	kJ/kg of fuel	%
Input energy				
1. Chemical energy in fuel	8819	99.4	8819	99.2
2. Electrical work	58	0.6	73	0.8
Total	8877	100	8892	100
Output energy				
In superheated steam	5293	59.6	5154	57.9
Losses				
1. Energy loss with dry fuel gas	961	10.8	1092	12.3
2. Energy loss due to free H in fuel	680	7.7	681	7.7
3. Energy loss due to moisture in fuel	1341	15.1	1347	15.2
4. Heat loss from boiler surface	39	0.4	48	0.5
5. Energy loss due to continuous blowdown	80	0.9	100	1.1
6. Unaccounted losses	483	5.4	470	5.3

Availability Analysis of Boiler

Availability balance equation for the boiler may be written as:

$$\begin{aligned} m_f a_{ch} + W_e = {} & m_s [h_4 - h_3 - T_o (s_4 - s_3)] + m_b [h_{sat} - h_3 - T_o (s_{sat} - s_3)] \\ & + m_m [h_6 - h_o - T_o (s_6 - s_o)] + m_g [C_{pa}(t_6 - t_0) - T_o \ell n (T_6/T_o)] \\ & + 9Hm_f [h_{fg} (1 - 1/T_{fg}) + h_6 - h_o - T_o(s_6 - s_o)] + I \end{aligned}$$

where
T_0 = ambient temperature in deg. K,
h_{fg} = latent heat of vaporization of moisture at T_{fg} deg. K,
s = specific entropy,
I = irreversibility,
a_{ch} = chemical availability of bagasse in kJ/kg,
= LHV[1.044 + 0.0013 H/C + 0.108 O/C + 0.0549 N/C] + 6.74 S

LHV = lower heating value of dry fuel, and
S = mass fraction of sulphur in the fuel.

Alternatively, the chemical availability of a fuel may be approximately estimated from

$$a_{ch} = 1.05 \text{ HHV}$$

where HHV = higher heating of the fuel.

The second law efficiency of the boiler,

$$\varepsilon = \frac{\text{availability increase in steam}}{\text{input availability}}$$

$$= \frac{m_s[h_4 - h_3 - T_0(S_4 - S_3)]}{m_f a_{ch} + W_e}$$

Results of the availability analysis of the boiler for the best and worst cases are shown in Table 2.

Table 2. Availability balance of boiler.

Availability	Best case		Worst case	
	kJ/kg of fuel	%	kJ/kg of fuel	%
Input availability				
1. Chemical availability of fuel	9,414	99.4	9,414	99.2
2. Availability with shaft work	58	0.6	73	0.8
Total	9,472	100.0	9,487	100.0
Output availability				
1. Availability output with superheated steam	2,018	21.3	1,940	20.4
2. Availability loss with continuous blowdown	18	0.2	22	0.2
3. Availability loss with flue gas	898	9.5	948	10.0
4. Availability loss due to heat transfer across the boiler surface	3	0.0	3	0.0
5. Total irreversibility	6,535	69.0	6,584	69.4

Discussion

The first law efficiency of boiler no. 4 varied from 57.8% for the worst case to 59.6% for the best case. The second law efficiency of the boiler in Table 2 confirmed the same trend. The total energy loss in the dry flue gas accounted for about 32% of the total energy input. On the other hand, from Table 2, availability in the flue gas is only about 10% of the total input availability. Since the bagasse had a very high moisture content, the energy loss due to the moisture was almost 14% of the total energy input. It is therefore logical to conduct a feasibility study on drying by waste energy recovery from the flue gas.

From the flue gas analysis, it was found that the amount of excess air used for combustion sometimes reached a value of 140%. If the amount of the excess air were kept at about 110% which still yielded complete combustion, energy loss with the flue gas could have been reduced.

Whilst Hugot [3] recommends that for the best boiler efficiency the excess air should be set at 50%, there was no opportunity in this study to try the excess air at the recommended value owing to a rather short milling season.

FEASIBILITY OF BAGASSE DRYING

In most sugar mills, excess amounts of bagasse are left from internal uses in the mills. Mill operators are therefore not too concerned with low boiler efficiencies. However, in the case of the sugar mill under investigation, the mill owner also operates a bagasse-board factory downstream. At present, an additional amount of bagasse has to be purchased from other sugar mills at a cost of 250 baht/ton to supply the bagasse-board factory. Hence, saving of bagasse by increasing the boiler efficiency would be very welcome.

From the previous section, the boiler analysis indicated that moisture in the bagasse used as the boiler fuel represented one of the major energy losses in the boiler at about 13.7% of the total energy input. A flue gas temperature of about 200°C would be sufficiently high for bagasse drying which would subsequently raise the boiler efficiency and reduce the amount of bagasse required as fuel for the same steam requirement in the sugar mill.

Bagasse Drying Analysis

The control volume of bagasse drying by the flue gas is shown in Fig. 3. Two assumptions are made in the analysis:

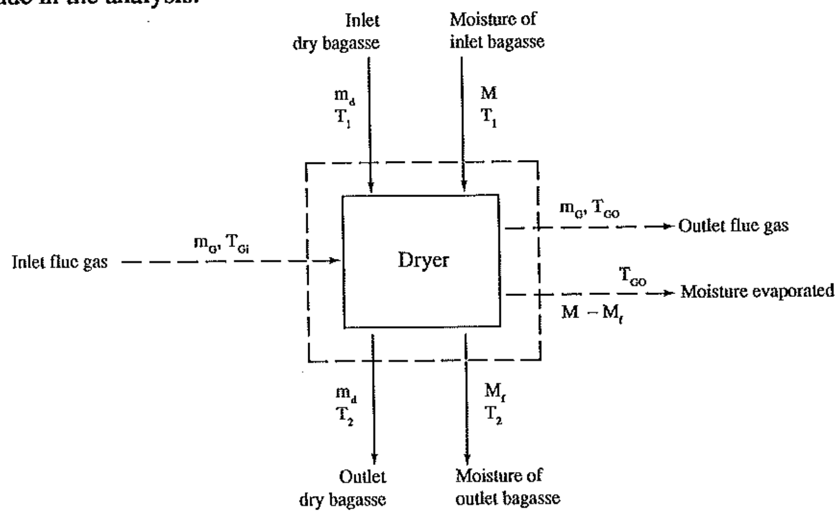

Fig. 3. Control volume of flue gas drying of bagasse.

(i) The moisture in bagasse evaporates at a steady rate.
(ii) Heat loss at the surface of the dryer, i.e. control volume is very small as a result of good insulation and is therefore neglected.

Energy balance equation for the dryer contains the following streams:

Enthalpy decrease in the flue gas

$$= m_G C_{pG} (t_{Gi} - t_{Go})$$

where m_G = mass flow rate of the flue gas,
C_{pG} = specific heat of the flue gas, and
t_{Gi}, t_{Go} = inlet and outlet temperatures of the flue gas.

Enthalpy increase in the dry bagasse

$$= m_d C_d (t_2 - t_1)$$

where m_d = mass flow rate of the dry bagasse,
C_d = specific heat of the dry bagasse,
t_1, t_2 = inlet and outlet temperatures of the dry bagasse.

Enthalpy increase in moisture

$$= M_f h_2 + (M - M_f) h_{Go} - M h_1$$

where M, M_f = initial and final moisture contents in the bagasse at the temperatures t_1 and t_2, and
h_1, h_2, h_{Go} = specific enthalpies of H_2O at t_1, t_2 and t_{Go}.

The energy balance equation for the bagasse dryer can be written as

$$m_G C_{pG} (t_{Gi} - t_{Go}) = m_d C_d (t_2 - t_1) + M_f h_2 + (M - M_f) h_{Go} - M h_1$$

A heat exchanger equation may be set up by means of the heat exchanger effectiveness, ε defined as

$$\varepsilon = \frac{\text{Actual heat transfer, } Q_{actual}}{\text{Maximum possible heat transfer, } Q_{max}} \tag{3}$$

The actual heat transfer can be estimated from either side of Equation (3). As the heat capacity of the dry bagasse is smaller than that of the flue gas, the maximum possible heat transfer is then

$$Q_{max} = m_d C_d (t_{Gi} - t_1) + M_f (h_{f,Gi} - h_1) + (M - M_f) (h_{Gi} - h_1)$$

where $h_{f,Gi}, h_{Gi}$ = specific enthalpies of saturated water and steam at t_{Gi}.

Hence
$$\varepsilon = \frac{m_G C_{pG}(t_{Gi} - t_{Go})}{M_d C_d (t_{Gi} - t_1) + M_f (h_{f,Gi} - h_1) + (M - M_f)(h_{Gi} - h_1)} \tag{4}$$

The amount of bagasse saving

$$= \frac{\text{Total energy transferred from the flue gas, } m_G\, C_{pG}(t_{Gi} - t_{Go})}{\text{Higher heating value of bagasse as fired, HV}} \tag{5}$$

From the above equations, the amount of bagasse saved per milling season can be estimated. During the milling season 1985/86, the sugar mill operated for 96 days and 24 hours per day. The possible savings of bagasse at various values of dryer effectiveness are estimated and shown in Fig. 4. The variation of the predicted flue-gas outlet temperature is also plotted in Fig. 5.

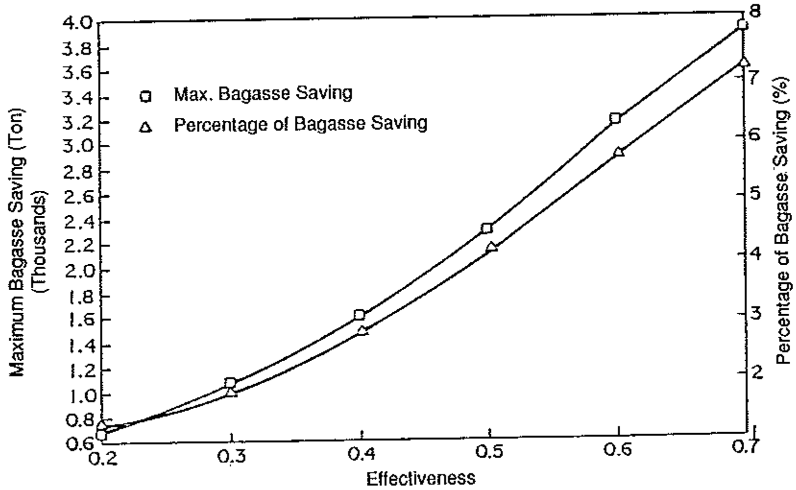

Fig. 4. Variations of maximum bagasse saving and percentage of bagasse saving with effectiveness.

Maximum Permissible Cost of Dryer

A Thai investor would be interested in the maximum permissible cost of the bagasse dryer that will yield a pay back period within two years. If the pay back period is greater than two years, the investor probably has to be encouraged by a government incentive.

As an example, if the effectiveness of the dryer is chosen as 0,7, then from Fig. 4, the maximum possible saving of bagasse is 3,905 tons per milling season.

Current price of bagasse purchased	=	250 baht/ton
(Note : 1 US$ ≅ 25 baht)		
Total benefit from the bagasse saved per year	=	3,905 x 250
	=	976,350 baht

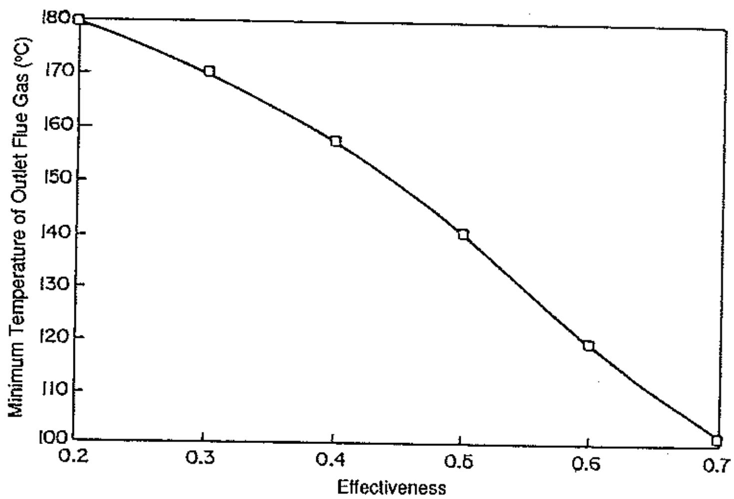

Fig. 5. Variation of minimum temperature of outlet flue gas with effectiveness.

Let the maximum permissible cost of the dryer	=	C baht
Capital Recovery Factor [4] at 15% interest and for a period of two years	=	0.615
Annual cost of the dryer	=	0.615 C

Power required by the fan of the dryer is assumed to be 20% of the power of 440 kW consumed by the induced draft fan for the boiler as the pressure loss in the dryer would be much less than that in the boiler. Assuming that the sugar mill operates for 96 days and 24 hours per day, the annual amount of electricity consumption is

$$= 0.20 \times 440 \times 96 \times 24 = 202{,}752 \text{ kWh}$$

Cost of electricity generated at the sugar mill/kWh	=	0.576 baht [5]
Hence, annual cost of electricity	=	202,752 x 0.576
	=	116,785 baht

Annual maintenance cost is estimated at 50,000 baht, which is about the same as that of the boiler. The economic equation using the annual cost method in this case is :

Total annual cost	=	total annual benefit [4]
0.615 C + 116, 785 + 50,000	=	976,350
C	=	1,316,112 baht.

By assuming a different value of dryer effectiveness, a corresponding permissible cost of the dryer can be determined by the same procedure. Variations of the maximum permissible cost of the bagasse dryer with its effectiveness are shown, in Fig. 6 for pay back periods of two and five years.

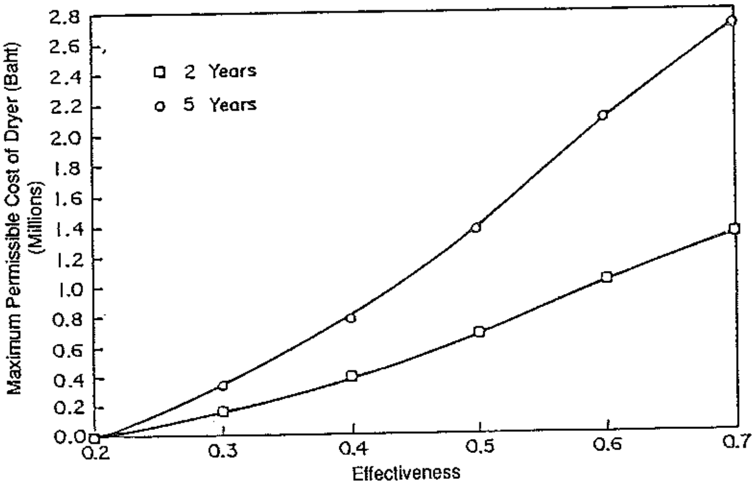

Fig. 6. Variations of maximum permissible cost of dryer with effectiveness (Interest rate =15% per annum for both cases).

Discussion

Prediction of possible bagasse saving through bagasse drying by the flue gas indicates that a considerable amount of money can be saved at the bagasse board factory. As an example, if a bagasse dryer of 0.7 effectiveness is used, 976,000 baht could be saved per milling season with an investment of 1,316,000 baht at 15% interest rate and a pay back period of two years.

The remaining task is to identify a real dryer whose price lies within the maximum permissible cost subject to an acceptable pay back period. If the bagasse dryer is in the form of a moving grate or rotating kiln, local fabrication of such a dryer to meet the above cost limitation seems possible. It should also be mentioned that if the estimated pay back period of an imported waste-energy recovery equipment lies within two to five years, an import duty reduction of about 20% of the equipment cost can be requested from the Ministry of Science, Technology and Energy.

CONCLUSIONS

The maximum efficiency of the bagasse-fired boiler in this study was only 59.6%. The energy loss in flue gas was 32% of which almost 14% was due to the moisture in the bagasse.

The downstream bagasse board factory purchases an additional amount of bagasse from other sugarmills at a cost of 250 baht/ton. Bagasse saving at the boiler is therefore desirable. A feasibility study of bagasse dryer using the flue gas shows that a considerable amount of bagasse and hence money can be saved if a real dryer whose cost lies within the maximum permissible value, subject to an acceptable pay back period, can be identified.

Other sugar mills that do not operate any downstream bagasse board factory can also benefit from bagasse drying since bagasse can also be sold to paper manufacturers.

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