THERMOHIDRAULIC DESIGN AND ECONOMICAL ANALYSIS OF A HEAT RECOVERY PROCESS IN A FLUIDIZED BED HEAT EXCHANGER

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Abstract. *This work describes the design methodology for a shallow fluidized bed heat exchanger applied for heat recovery from hot gas exhausted by a boiler. Averaged data from a food industry were used for the heat exchanger design and to simulate the economical results. Economic Engineering analysis was conducted for each proposed situation in order to evaluate the economic feasibility and investment for the manufactoring and installation of the heat exchanger obtained from design. The heat exchanger works with bubbling fluidized bed and sand was used as the inert solid material. The solid particles are suspended by the boiler exhaustion gas producing a gas-solid fluidized bed that heats up boiler make-up water flowing inside immersed tubes. The considered heat exchanger allows the pre-heating boiler make-up water through the heat recovery from hot gas exhausted by the own boiler. To evaluate the proposed equipment, it was used the net present value (NPV) method and the internal rate of return (IRR) method. Final results showed the economical effects and the reduction potential concerning fuel consumption for the proposed productive process.*

Keywords: *heat recovery, economical analysis, fluidized bed*

1. Introduction

Historically, mankind economical development was always linked to the increase of energy consumption. However, energy consumption current levels have brought about a general concern on the decrease of the natural resources and resultant environmental impacts. The natural resources are scarcer and the energy becomes more important in the composition of industrial products costs. More efficient the productive processes, less energy is necessary, therefore the search of the best thermal efficiency of the processes will save energy for the industry and will allow the preservation of several common sources of energy. In agreement with the Brazilian Energetic Bulletin (Brazil, 2003), 14% of all primary energy produced in Brazil is from hydraulic origin and the remaining is originated from burning processes of several fuels like mineral coal, natural gas, petroleum and biomass (alcohol, vegetable residues, pulp, etc.). The industrial segment consumes about 52% of all primary energy produced in Brazil, and 70% of that energy is derived from fuels. These numbers show that the development of intensive actions for reducing thermal energy consumption in Brazilian industries can be very important for the country's economy. This paper shows the example of a boiler to demonstrate the economical benefits obtained by an improvement in the process through the addition of a heat exchanger at the hot gas outlet. The design methodology for a shallow fluidized bed heat exchanger is shown too, as well as the related economical benefits for the industry.

2. Flow chart proposal

The studied process consists of a steam boiler of a food industry located at Paraná state in Brazil. The steam is generated in an aqua-tubular boiler type. The boiler, showed in the flow chart (Fig. 1), is operated with saturated steam at 2,333kPa work pressure and nominal capacity of 45,000kg/h. The boiler uses natural gas as fuel. The flow's data can be verified in Tab.1. It is observed from Tab. 1 that flow 4 (boiler exhaustion gas) still presents a great energy potential, allowing a possible improvement opportunity. This observation has brought about the idea of the installation of heat recovery equipment at the boiler gas outlet. The flow chart proposal is showed in Fig. 2 and proposal flow's data in Tab.2.

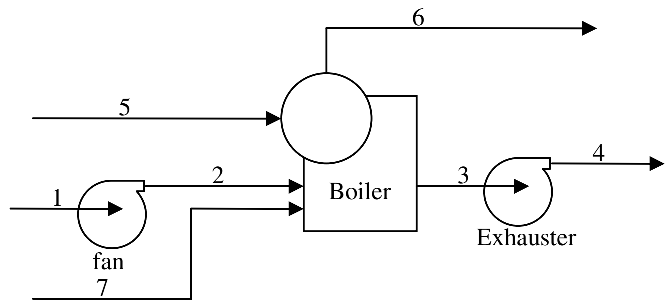

Figure 1. Actual flow chart

Table 1. Flow data and properties

Flow	1	2	3	4	5	6	7
Fluid	Air	Air	Gas	Gas	Water	Steam	Fuel
Temperature [°C]	25	25	320	320	105	220	25
Pressure [kPa]	92	93.5	89.5	92	2,333	2,333	92
Flow [kg/s]	14.7	14.7	15.37	15.37	9.83	9.83	0.63

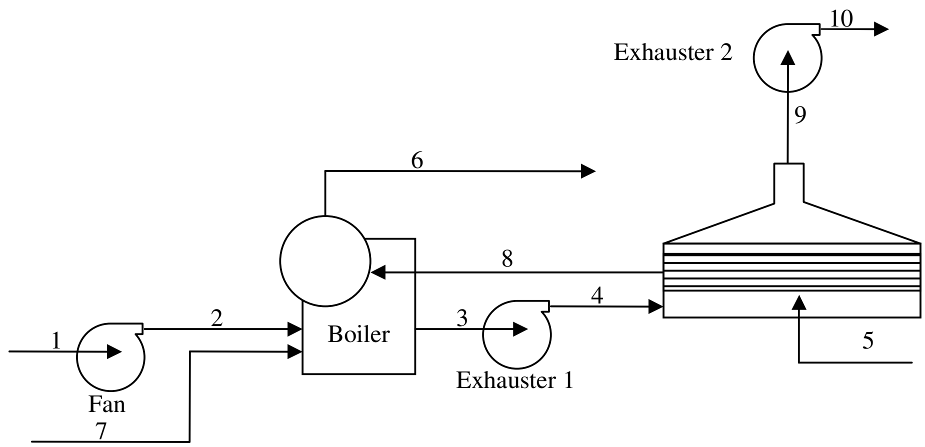

Figure 2. Flow chart proposal

Table 2. Flow data and properties proposal

Flow	1	2	3	4	5	6	7	8	9	10
Fluid	Air	Air	Gas	Gas	Water	Steam	Fuel	Water	Gas	Gas
Temperature [°C]	25	25	320	320	105	220	25	150	180	180
Pressure [kPa]	92	93.5	89.5	96.1	2,333	2,333	92	2333	89.5	92
Flow [kg/s]	14.7	14.7	15.35	15.35	9.83	9.83	0.61	9.83	15.35	15.35

3. Heat Exchanger Design

The specification includes process data, mechanical design data and considerations about involved materials (Pécora et al, 1998). The process data consist of mass flow rate, pressure, temperature, fluids composition and phase, thermal loads, acceptable pressure losses. For the geometric design some preliminary definitions were taken into account, as the objective is a heat exchanger design showing the smallest platform area together with low pressure drop. The bed height

(H_L) must be small for assuring small bed pressure drop, but it must be large enough to maintain al the tube array immersed in the fluidized bed.

The following hypotheses were adopted:

- Steady state regime;
- Uniform bed temperature;
- The bed temperature (T_L) is the arithmetic average considering gas temperature at the inlet ($T_{g,i}$) and outlet ($T_{g,f}$) positions;

$$T_L = \frac{T_{g,i} + T_{g,f}}{2} \quad (1)$$

- The heat transfer rate for the water flow corresponds to the heat transfer rate from the gas (adiabatic heat exchanger).

3.1. Cross section area of the fluidized bed (*S*)

The cross section area of the fluidized bed (S) corresponds to the product between the width (B) and the length (L) of the heat exchanger (Rodriguez, 1998). Besides:

$$S = \frac{\dot{m}_g}{\rho_g . u_0} \quad (2)$$

Where $\dot{m}_g$ and ρ_g refer to the mass flow rate and density of the gas, respectively. The superficial gas velocity (u_0) was assumed as twice the minimum fluidization velocity following literature data that indicate this velocity as the best one concerning the heat transfer process between fluidized gas-solid suspension and tube wall.

The minimum fluidization velocity was obtained through the equation of Ergun with the classical approach of Wen and Yu (1966):

$$u_{mf} = \frac{\mu_g}{d_p . \rho_g} \left\{ \left[33.7^2 + \frac{0.0408 . d_p^3 . \rho_g . (\rho_s - \rho_g) . g}{\mu_g^2} \right]^{1/2} - 33.7 \right\} \quad (3)$$

Where μ_g, *g*, ρ_s *e* *dp* refer to the gas dynamic viscosity, gravitational acceleration, solid particles density and mean diameter, respectively. All units are expressed in the S.I. system.

3.2. Heat transfer area between gas-solid suspension and tube wall (*A*)

The necessary heat transfer area (A) can be obtained from the desired values for the outlet temperatures for the gas and water flows (T_{gf} and T_{af}), besides the available water and gas mass flow rate in the process ($\dot{m}_a$ and $\dot{m}_g$).

The heat transfer rate to the water flow inside the immersed tubes ($\dot{Q}_a$) is obtained through Eq. (4):

$$\dot{Q}_a = \dot{m}_a . c_{p,a} . \left(T_{a,f} - T_{a,i} \right) \quad (4)$$

Assuming an adiabatic heat exchanger with one pattern inside the tubes and a constant heat transfer coefficient, the heat transfer rate across the surface area *A* may also be expressed as

$$\dot{Q}_a = U . A . DMLT \quad (5)$$

Neglecting the thermal resistance of the tubes wall, the average global heat transfer coefficient (*U*) is obtained from the heat transfer coefficient inside the tubes (h_a) and the suspension-tube heat transfer coefficient (h_{mp}):

$$\frac{1}{U} = \frac{1}{h_{mp}} + \frac{d_e}{h_a . d_i} \quad (6)$$

Where d_e and d_i refer to the external and internal tube diameter, respectively.

The logarithmic mean temperature difference (LMTD) is calculated according to Eq. (7):

$$LMTD = \frac{(T_L - T_{a,f}) - (T_L - T_{a,i})}{\ln\left(\frac{T_L - T_{a,f}}{T_L - T_{a,i}}\right)} \tag{7}$$

The maximum value of the suspension-tube heat transfer coefficient ($h_{mp,máx}$), for particles of the Geldart´s B group, is according to Zabrodsky et al. (1976) obtained by Eq. (8) where the units should be from S.I.

$$h_{mp,máx} = 35.8.\left(\rho_s^{0.2}.k_g^{0.6}.d_p^{-0.36}\right) \tag{8}$$

In agreement with Botterill (1986), the average value of h_{mp} is around 70% of the calculated value obtained from Eq. (8) concerning immersed tubes in fluidized beds.

The water heat transfer coefficient inside the tubes (h_a) can be obtained from Incropera and DeWitt (1996).

Assuming the length/width ratio (L/B) of the heat exchanger from available area for the equipment in the industry, we can calculate the heat exchanger length (L), that corresponds, as a first approach, to the tubes length crossing the heat exchanger.

$$L = \sqrt{S.(L/B)} \tag{9}$$

The number of immersed tubes (n_t) immersed in the fluidized bed can be obtained from the heat transfer area calculated through Eq. (5):

$$n_t = \frac{A}{\pi.d_e.L} \tag{10}$$

The height of the fluidized bed (H_L) is obtained for a given tube arrangement and tube pitch once the gas-solid suspension should cover all the tubes.

3.3. Pressure drop and power gas pumping

The shell side pressure drop (ΔP) is calculated as the sum of the pressure drop due to the distributor plate (ΔP_d) and due to the fluidized bed (ΔP_L):

$$\Delta P = \Delta P_d + \Delta P_L \tag{11}$$

The distributor pressure drop can be obtained through the correlation proposed by Basu (1984):

$$\Delta P_d = 0{,}1 + 0{,}2.\exp(-De/2).H_L \tag{12}$$

Where *De* is the bed equivalent diameter, calculated by:

$$De = \frac{4.S}{2.L + 2.B} \tag{13}$$

The pressure drop in the fluidized bed was assumed due to the weight of the solid particles:

$$\Delta P_L = \rho_S.(1 - \varepsilon_{mf})g.H_L \tag{14}$$

Where ε_{mf} is the bed porosity in the minimum fluidization condition.

The necessary pumping power ($\dot{W}_b$) can be calculated by Eq. (15):

$$\dot{W}_b = \frac{\Delta P \cdot \dot{m}g}{\rho_g} \tag{15}$$

The distributor plate should assure the bed uniformity and the methodology proposed by Basu(1984) can be used for perforated plates or gruyere distributors.

4. Advantages after installation

The proposed methodology was applied to the flow chart showed in Fig. 2, concerning data from Tab. 1. It was assumed L/B=2/3 and tubes with nominal diameter of ¾" because it is a common diameter which fits well the considered mass flow rates.

A heat exchanger was designed considering $T_{g,f}$ as 180°C and the make-up boiler water heated from 105°C to 150°C. Such heat save allows a reduction in the amount of fuel consumed in the boiler, as demonstrated in Tab. 3.

Table 3. Comparison between actual and proposal flow chart

Parameter	Actual	With heat exchanger
Fluid	Water	Water
Temperature [°C]	105	150
Pressure [kPa]	2,333	2,333
Mass flow rate [kg/s]	9.83	9.83

Through Tab. 3 data and considering the hypothesis that the boiler efficiency will be maintained constant, it will be observed a reduction of 5.6% in the fuel consumption, which means an economy around 400,000m^3/year.

5. Investiments

The investments were evaluated comparing with similar equipment, suppliers quotations prices, as well as recommendations presented by Bejan et al. (1996). Table 4 shows the necessary investment values for the proposal alternative.

Table 4. Investments

I. Fixed investments		R$559,773.00
A. Direct Cost	76%	R$477,600.00
1. Equipment	48%	R$300,000.00
2. Pipes (15% of A.1)	7%	R$45,000.00
3. Instrumentation & Control (12% of A.1)	6%	R$36,000.00
4. Electric material (60% of A.3)	3%	R$21,600.00
5. Building (5% of A.1)	2%	R$15,000.00
6. Labor (20% of A.1)	10%	R$60,000.00
B. Indirect Cost	13%	R$82,173.00
1. Engineering & Supervision (12% of I)	11%	R$67,173.00
2. Miscellaneous (5% of A.2)	2%	R$15,000.00
II. Other Costs	11%	R$68,543.00
Start up (10% of I)	9%	R$55,977.00
Working Capital (2% of Grand Total)	2%	R$12,566.00
Total		R$628,316.00

6. Results and Discussion

6.1. Heat Exchanger data

The main design data of the heat exchanger are shown in Tab. 5. Calculations were made considering sand particles with mean diameter (d_p) of 500μm as the solid particles inside the fluidized bed.

Table 5. Heat Exchanger data

Parameter	Value	Unit
Minimum fluidized velocity (u_{mf})	0.148	m/s
Superficial gas velocity (u_0)	0.295	m/s
Cross section area of the fluidized bed (S)	88.57	m^2
Heat transfer area (A)	64.9	m^2
Total length of the pipes	1,095	m
Heat transfer rate between mixture gas-solid and wall (h_{mp})	268.6	W/m^2K
Heat transfer rate of the inside of the pipes (h_a)	2,234	W/m^2K
Shell side pressure drop (ΔP)	6.59	kPa
Power pump ($\dot{W}_b$)	232.3	kW

6.2. Economical analysis

The techniques used in this work to evaluate the investments were the net present value (NPV) method and the internal return rate (IRR) method.

The Net Present Value (NPV) method calculates the current revenue value and the expenses in a cash flow, for each investment alternative, considering the Minimum Attractive Rate of Return (MARR). The characteristic value of the alternative is the difference between the current revenues values and expenses. If the difference is positive, the return rate of the invested capital is larger than MARR. However, if the difference goes negative, the investment won't be attractive, because the return rate of the capital will be smaller than MARR (Casarotto and Kopittke, 1996).

The internal return rate (IRR) method consists on evaluating the interest rate which cancels the difference between updated incomes and expenses cash flow values. The higher the rate of return, the earlier to recover invested capital and, consequently, the lower the risks for the investor. An investment alternative will be considered attractive if the rate of return is higher than the MARR. Evidently, in an investment risk analysis, the choice will be for the alternative with the highest return rate (Casarotto and Kopittke, 1996).

Some concepts are important in the Economical Engineering. The Cash Flow, the Minimum Attractive Rate of Return (MARR) and the Depreciation are concepts without which we can't execute an investment analysis. The cash flow (of a company, of an investment, of an individual, etc.) means the group of entrances (revenues) and exits (expenses) of money along the time (Puccini, 1995). The Minimum Attractive Rate of Return of an investment is the minimum value of the interest rate for the which suits the investor to choose in certain investment project. That corresponds, in practice, to the rate offered by the market for a capital application, as the deposits to fixed period, stock exchange, etc. (Puccini, 1995). The difference between the price of purchase of a good and its change value (residual value) at the end of a certain time, is called Depreciation (Puccini, 1995).

Table 6 shows the economical analysis obtained from flow chart proposal, considering revenues and payments as maintenance, working capitals and depreciation of the investment (Brazil, 1999) as well as economic indicators (Hess et al., 1980).

Table 6. Cash Flow

YEAR	R$
0	(467,615,42)
1	171,408.57
2	178,591.89
3	183,580.19
4	188,718.15
5	194,010.24
6	199,461.10
7	205,075.49
8	210,858.30
9	216,814.60
10	222,949.59
MARR	18%
IRR	38%
NPV	326,800.20

The values obtained are suitable to the conditions usually found in industry and the values are similar to other equipment designs shown by literature. Such results demonstrate the technical feasibility of the presented proposal.

In the financial analysis of the investment, Tab. 6, the proposed equipment showed an internal return rate around 38%/year, presenting a net present value of R$ 326,800.20. Such results are adequate for a good investment because the value of the internal return rate is larger than the minimum attractive rate of return, as well as the net present value is positive. Therefore at the end of the investment depreciation, the net balance will be positive, considering the minimum attractive rate of return.

Through the obtained results and observing the technical aspect or the financial aspect as well, the flow chart proposal is feasible and can be implemented by industry.

6. Conclusion

The results were shown quite promising, indicating that the fluidized bed heat exchanger can be quite an attractive alternative for heat recovery from hot exhausted gases. Such equipment also presents financial profit provided by reducing energy consumption in the industry.

Further studies about the subject can be made comparing the fluidized bed heat exchanger with a conventional heat exchanger used for heat recovery from hot gases.

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