EXERGY ANALYSIS OF SOYBEANS DRYING PLANTS WITH COGENERATION OR TRIGENERATION

Fábio Antônio Filipini
Federal University of Paraná, PIPE, Curitiba - PR
e-mail: bellcwb@terra.com.br

George Stanescu
Federal University of Paraná, Mechanical Engineering Department, Curitiba - PR
e-mail: stanescu@demec.ufpr.br

Marcelo Risso Errera
Federal University of Paraná, Department of Transportation, Curitiba - PR
e-mail: errera@ufpr.br

Abstract. *This paper presents an exergy analysis of industrial soybeans drying plants. The main purpose of the analysis was to verify whether cogeneration and trigeneration alternatives can increase exergy efficiency of such plants. Cogeneration configuration (just to meet power needs) yields drying heat load while electricity is generated. Trigeneration provides cool thermal energy in addition to heat and electricity. A reference plant has a continuous mixed-flow direct-fired column dryer with forced-air drying and cooling. Such features are found in most corn and soybeans dryers in the industry. A flow regime of 100 t/h of soybeans was set, even though dryers can operate up to 500 t/h. The dryer studied was divided into four control volumes, namely, (1) the heater/burner, (2) the mixing chamber, (3) the cooling chamber and (4) the drying "zone". Technical specification matches those of most Brazilian manufacturers. Microturbines were considered for cogeneration and an assembly of stationary fuel cell and water chiller was considered in the trigeneration plant. The exergy analysis was based on simulations of three different energetic alternatives performed in Stanescu et al (2003). Results are presented in tables and Grassmann charts. The reference drying plant showed an exergetic efficiency of 5%, and little gain is obtained when cogeneration is introduced. Trigeneration also presented little gain, but raised exergetic efficiency as high as 8%; a relative gain of 60%. The cogeneration configuration presented the highest energy efficiency. The dissipative nature of drying plant prevails if cogeneration or trigeneration are in low levels of power generation. Results based on the exergy analysis presented in this paper will be the basis of a thermoeconomic analysis and technical feasibility studies of natural gas as an alternative fuel for food industries.*

Keywords. *Soybeans dryers, exergy analysis, natural gas, cogeneration, trigeneration.*

1. Introduction

This papers presents energetic and exergetic analyses a soybean drying plant. Such plants operate at high thermal load in an intrinsically dissipative process (heat to remove moisture). Even though energy efficiency can be near 75%, very low exergetic efficiency may be expected if ordinary fuels are burnt. One solution that comes to mind is to rationalize the way high-grade thermal energy is downgraded to 60 °C, temperature under which soybeans must be dried in order to hold commercial quality.

In order to shed some light in this matter, first a drying plant must be analyzed in view of its energy and exergy performance. After that cogeneration and trigeneration are then studied. Performances are compared and conclusions are drawn.

A "reference" drying plant was the basis for comparing energy alternatives. Microturbines (low level of power generation) are added on the drying plant to make it work under cogeneration. Trigeneration is achieved by adding an assembly of stationary fuel cell and hot-water chiller on the reference plant.

A continuous mixed-flow direct-fired column dryer with forced-air drying and cooling was selected to be the main equipment of the reference drying plant. Such features are found in most corn and soybeans dryers in the industry. A flow regime of a 100 t/h of soybeans was set, nevertheless dryers can operate up to 500 t/h.

Models were devised to simulate all the three plant configurations covered in this study. The reference plant was divided into four control volumes, namely, (1) the heater/burner, (2) the mixing chamber, (3) the cooling chamber and (4) the drying "zone". Additional control volumes were added on when cogeneration and trigeneration were introduced. Complete details of those models and the mathematical (numerical) procedures used are also being presented in this meeting (Stanescu et al, 2003). Parts of those models were first developed in Filipini (2002).

Exergy analyses were carried out for each one of the three alternatives. Results were summarized in tables and illustrated in Grassman type charts.

This study leads to the conclusion that low levels of cogeneration are not enough to improve exergy efficiency of a drying plant when typical fuels are used, that is, this is a case of great mismatch between energy source and the purpose of the process. Attempts to improve exergy efficiency of such plants ought to compensate the intrinsically dissipative nature of the processes involved.

2. Description of the processes of the soybeans "reference" dryer

Recently a survey identified typical equipments and operating conditions of grain drying plants in the State of Paraná (Errera et al, 2003). Most of the equipments were made within Brazil and are very similar. Drying plants operate with up to three dryers. Commercial dryers can operate from 100 to 500 t/h of soy and corn beans. A typical dryer was chosen as reference case. The operation regime was set to 100 t/h since scale was not relevant for the purposes of the present study.

The drying process is very peculiar and by no means trivial. While drying plants operate around the clock during the harvest season, and loaded trucks queue up along the highways, grains cannot be injured mechanically neither dried abruptly. Drying cycles are carefully established for each kind of grain. Drying process is controlled mechanically and thermally. For instance, drying temperature cannot exceed 60 °C for soybeans.

Usually soybeans leave the fields with 18% of moist content and must be dried out until 13%. The thermal energy load to dry 100 t/h of soybeans is about 4.000.000 kcal/h (266kW) and 65 kW of electricity (Errera et al, 2002).

The core of the dryer is formed by a stack of horizontal staggered air ducts. Grains are loaded at the top and then fall down by gravity in cross flow with the air of the ducts stack. One third of that stack is dedicated to the cooling chamber, where ambient air is pre-heated while cooling warm soybeans. Studies (e.g., Errera et al, 2002) recommend that soybeans should not leave the dryer as warm as five degrees above ambient temperature. Such operational requirement relies on the fact that possible moisture re-absorption may take place and storage potential is degraded.

Figure (1) illustrates the main features of the drying plant under discussion. Wide arrows show air flow. Ambient air, flow (6), is drawn into the dryer, and then cools warm dry-soybeans, and ultimately it is mixed with hot combustion gasses.

The reference plant of Fig. (1) is divided into four control volumes. The theoretical structure, as well as detailed chemical species flows are shown in Fig. (2). Heat and electricity fluxes are also shown. Potential and kinetic energies are negligible. In the drying process water partial pressure plays major role since it is the driving mechanism of moisture removal. Hence a detailed calculation of water partial pressures is performed since ordinary psicrometric calculations do not apply.

More comments on the mathematical model are presented in the next section.

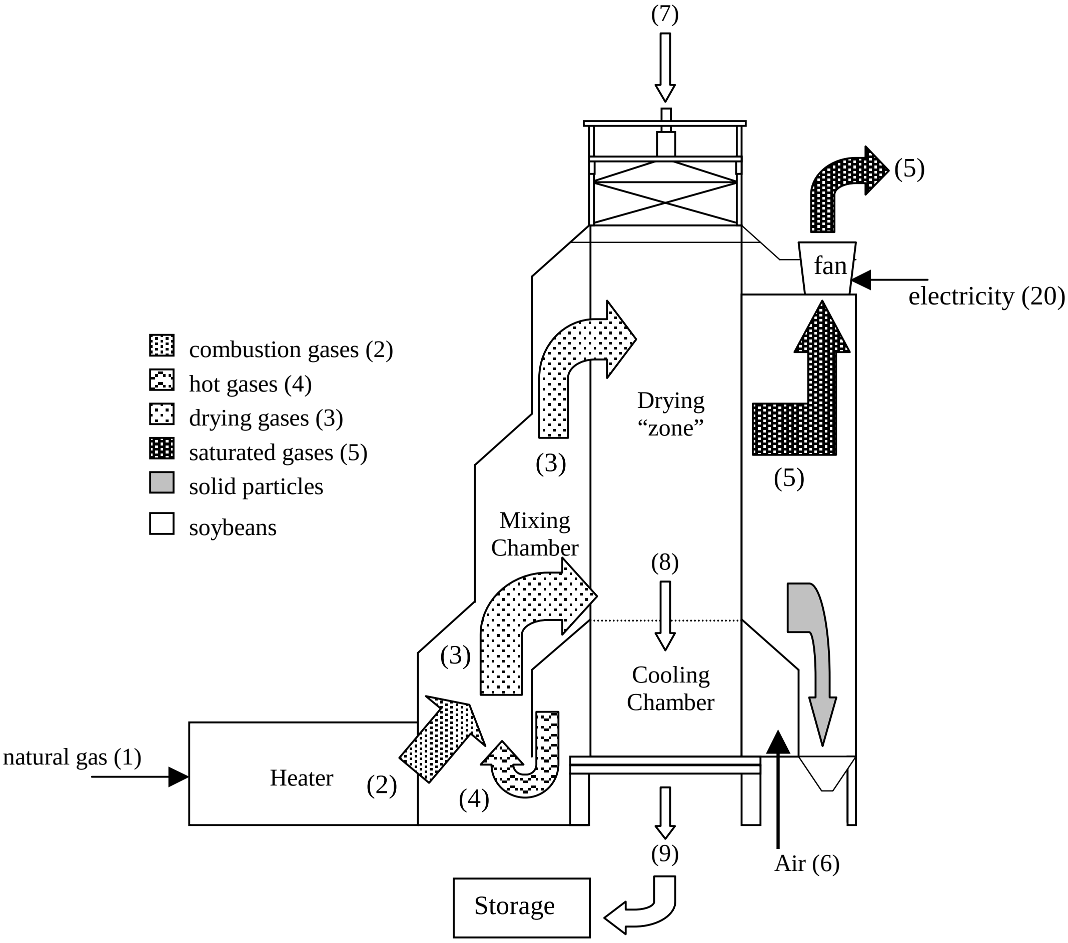

Figure 1. Schematic view of the "reference" industrial dryer considered in this study.

3. Mathematical model and simulations

Studies of energy and exergy performance rarely need to account for transient issues, since it represents very little on the overall energetic performance of the plant. Therefore, only steady-state regimes are considered. A combination of manufacturers data, mass conservation principle and Thermodynamics (First and Second Laws and state correlations) made possible to calculate chemical species, enthalpy and exergy balances for each one of the four control volumes drawn in Fig. (2).

Wood and fuel oil are the most common fuel for such plants for many reasons, as for instance, gaseous fuels such LPG and natural gas (NG) have been unavailable or very expensive in the past. Nevertheless, Embrapa-Soja recommends gaseous fuels for high quality drying (Errera et al, 2002). Thus natural gas was selected as heat source for the drying process.

Natural gas (NG) was considered pure methane (CH_4). Natural gas is fully burnt such that all carbon is present as CO_2 and hydrogen is present as H_2O in the combustion gasses. Soybeans do not undergo any chemical reaction; they just exchange moisture with drying gasses. Pressure drop was considered negligible.

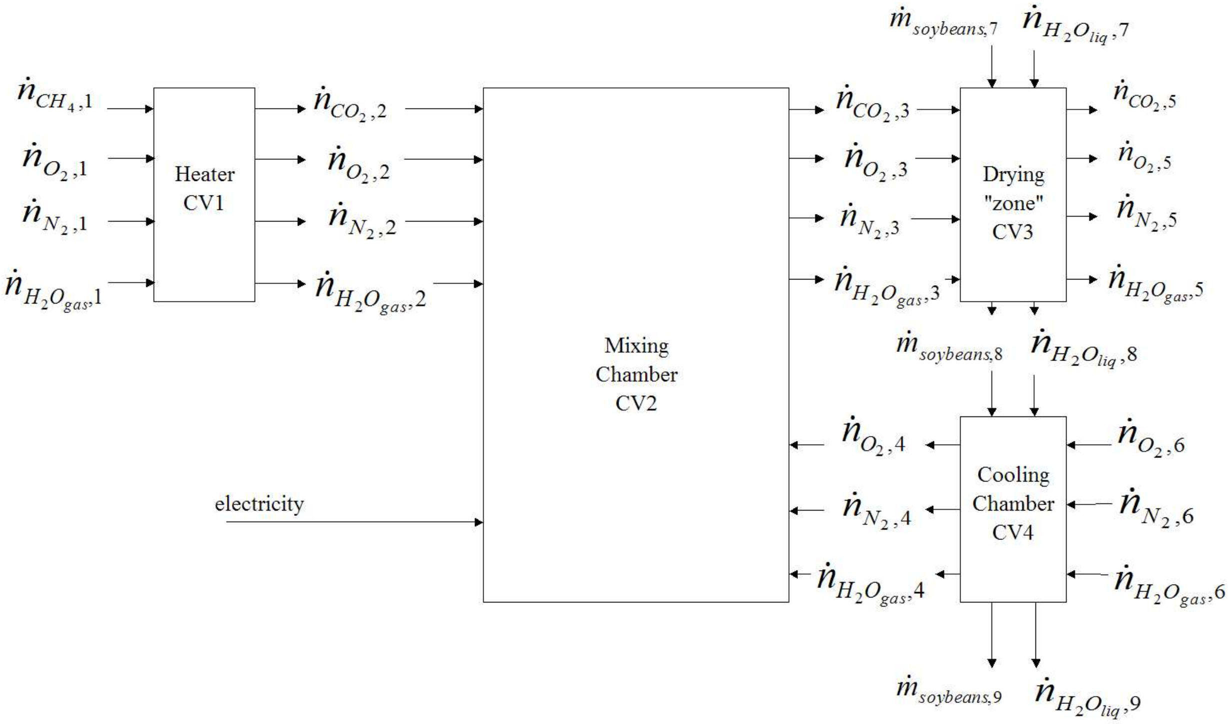

Figure 2. Control volumes and chemical species flows of the “reference” industrial dryer.

The physical principles lead to a non-linear system of equations that is solved for given parameters. Further details on the model, numerical procedures and simulations are available in Filipini (2002) and in Stanescu et al (2003).

Next sets of microturbines are added on the reference plant of Fig. (1) and the resulting cogeneration plant is discussed.

3.2. Soybeans drying plants with cogeneration

At the furnace temperatures can go as high as 1,500 °C when natural gas is burnt. The combustion gasses produced in the furnace must be mixed with air so it is cooled down to moderate temperature. The resulting gas mixture is often called “drying air”. Those combustion gasses must be mixed with air to cool down in order to constitute the so called “drying air”. One can identify the opportunity to improve exergy efficiency by introducing a heat engine to produce work as high grade thermal energy is downgraded to form the “drying air”. Cogeneration presented itself as good alternative.

In this section the cogeneration plant is presented and discussed. A low level of power generation is first considered, mainly to meet electricity needs of the dryer. A relative new product in marketplace called “called microturbine” was considered to be the heat engine.

Microturbines are devices that operate under an open-ended Brayton Cycle with natural gas as fuel. They are sold in modules of 30 and 60 kW (power).

Sets of microturbines are added on the reference plant of Fig. (1) and the resulting cogeneration plant.

The resulting new physical structure of the plant is shown in Fig. (3), where one can notice the fifth control volume that is related to the microturbines (e.g., a high-pressures gaseous fuel 330 Capstone Micro-Turbine^{TM}). In that control volume both heat and electricity are produced.

The performance of the cogeneration plant is discussed in section 5.2.

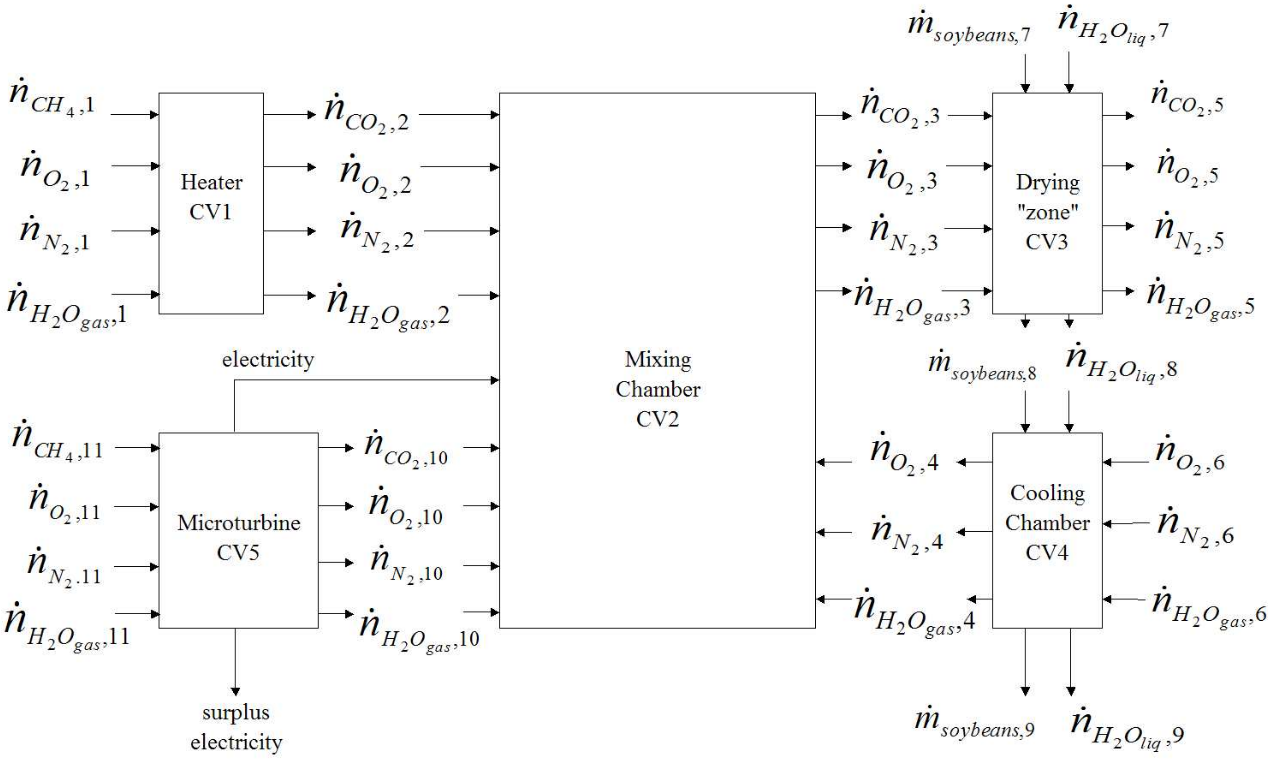

Figure 3. Physical structure of soybeans dryer with natural gas cogeneration.

3.3. Soybeans drying plants with trigeneration

Another promising solution to improve exergetic efficiency of the drying plant is to add auxiliary equipments to assembly a trigeneration system, that is, a plant that would produce electricity, thermal energy and cool energy. There are many ways a plant can be turned into a trigeneration plant. In this work the new technology of stationary fuel cells is considered. A stationary fuel cell is combined with a hot-water fired chiller and a set of microturbines.

The whole plant is still run solely by natural gas: part is burnt in the dryer furnace, part in the microturbines and part in partially burnt in the reformer of the fuel cell. It is worth mentioning in this paper that high efficiencies in the fuel cell with methane reformer can only be achieved if the waste hot-water is further utilized.

Figure (4) illustrates the new physical structure of the drying plant.

Under the trigeneration configuration, the total electricity generated surpasses the drying plant needs and can be utilized elsewhere in the plant site. The waste hot-water is further heated in the mixing chamber to feed the chiller. That last feature will contribute to overall efficiency by making use of a wasted exergy of the fuel cell (almost 50%) and will cool ambient air to speed up grains cooling in the cooling chamber.

The new configuration presented in Fig. (4) shows new control volumes, namely, CV6 – fuel cell (e.g., a ONSI Corporation PC25^{TM}C Fuel Cell) and CV7 – absorption chiller (e.g., a Yazaki Energy Systems, Inc WFC-10 water fired chiller) and CV8 – heat exchanger to cool ambient air before it enters into cooling chamber. There are now eight control volumes.

4. Thermodynamic issues of the analyses

Studies like this one are based mainly on the thermodynamic property called exergy, which is a combination of energy (enthalpy) and entropy. It has been shown in the literature that exergy based studies are more likely to succeed in identifying critical energy conversion processes in a plant (e.g., Kotas, 1985, Bejan, 1996, among others). That is possible because exergy is not a conservative property such as energy. The main advantage of introducing the exergy concept is that one can keep track of the mismatches between energy source and the purpose of the process under study: the more exergy is destroyed greater is the mismatch. The amount of exergy destroyed is equal to the irreversibility produced in the process.

Exergy, energy and enthalpy are thermodynamic properties that should be calculated carefully. A complete discussion of all hypotheses considered to perform the calculations can be found in Filipini (2002), Stanescu et al (2003) and Errera (2002).

All the gaseous substances were modeled as ideal gas. Soybeans are assumed to be pure substances in way that a constant heat capacity could be used. Entropy and enthalpy of all substances were calculated based on the heat capacity of the gases, water and soybeans. The equations were typically:

$$h_T = \int_{T_0}^{T} c_{p0}\, dT \tag{1}$$

$$s_T^0 = \int_{T_0}^{T} \frac{c_{p0}}{T}\, dT \tag{2}$$

For convenience, the reference temperature was set as 0°C (273.15 K).

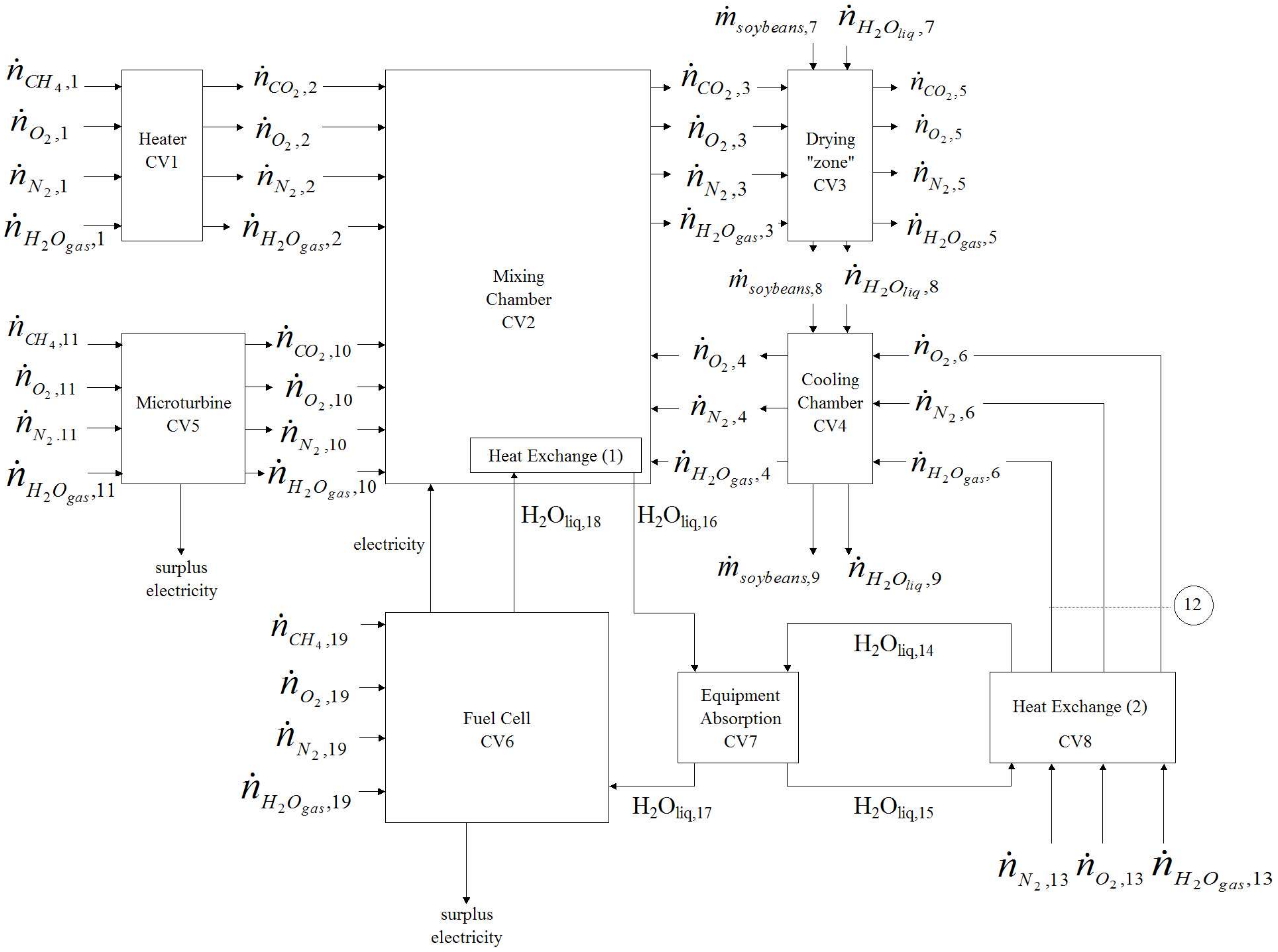

Figure 4. Physical structure of soybeans dryer with natural gas trigeneration.

Once mass flow, concentrations of chemical species, enthalpy and entropy were obtained, the exergy content of the flows were determined by the general equation below (e.g., Kotas, 1985):

$$\dot{E}_x = \dot{E}_x^{CH} + \dot{E}_x^{PH} \;=\; \dot{E}_x = \left(\sum_i Y_i E_i^{CH} + RT_0 \sum_i Y_i \ln \gamma_i Y_i\right) + \left((h - h_0) - T_0(s - s_0)\right) \tag{3}$$

where γ_i is the activity coefficient of chemical species i, and they are all equal to one in this case. The thermal component of the physical exergy is negligible and so is potential and kinetic component. Values of chemical exergy of the flows were obtained based on Model II^b, Table C.2 of Bejan (1996).

Irreversibilities were calculated by its equivalent called destroyed exergy, which is the difference in the exergy inventory on each one of the control volumes, thus:

$$I = \sum E_{x,in} - \sum E_{x,out} \tag{4}$$

All calculations were performed within the computer code such that conditions could be varied.

5. Energetic and exergetic analysis

In previous sections three different drying plants were introduced. The rationale behind the synthesis of each one of them was discussed. The mathematical model and the theoretical aspects were also reported. The overall result at this point is a computer code that can simulate three different energy configurations of drying plants in any operating condition. This section presents energy and exergy inventory of all three systems addressed in this study. Since plant operation management vary considerably from plant to another, all equipments of all three plants were considered to operate under design conditions.

The following sub-sections will present results and discussion of the inventories of the plants in the sequence: (i) Reference drying soybeans plant; (ii) Reference drying soybeans plant with cogeneration with microturbines; and (iii) Reference drying soybeans plant with trigeneration with microturbine, fuel cell and absorption chiller.

5.1 “Reference” drying soybeans plant

The first results concerns the reference drying plant. Table (1) presents the values of temperatures (pressure was nearly constant) and mass flows, as well as energy and exergy flow obtained from the numerical simulation.

Table 1. Temperature, mass, energy and exergy flows in design condition of the reference drying plant

flux	description	T °C	$\dot{m}$ kg/s	$\dot{E}$ kW	$\dot{E}_x$ kW
1	natural gas heater	20.00	2.82	6,305.89	5,758.30
2	combustion gases	1,503.45	2.82	6,068.43	3,614.17
3	drying gases	100.00	81.03	10,742.61	909.83
4	hot gases	39.35	78.21	4,893.42	245.26
5	saturated gases	31.50	82.42	8,607.08	312.67
6	air (6)	19.75	78.21	3,327.10	221.47
7	soybeans (7)	20.00	29.17	1,549.53	3.22
8	soybeans (8)	48.00	27.78	3,439.86	60.39
9	soybeans (9)	24.75	27.78	1,773.68	-
20	electricity	-	-	66.24	66.24

It is not an easy task to establish performance criteria in plants like the one under study. Kotas (1985) among others recommends the use of “rational” efficiency. In this case, the rational efficiency of the reference plant is best defined if the useful effect (purpose) of the plant is moisture removal, that is, the amount of moisture in flow (5), saturated gasses. The resources to accomplish that are natural gas, flow (1), air in flow (6), humid soybeans of flow (7) and electricity of flow (20). Therefore the energy efficiency of the reference plant is 76.52 %, while the exergetic efficiency is 5.17 %.

Figure (5) is Grassmann type diagram. It shows, graphically, that a major exergy destruction takes place in the mixing chamber, control volume (2). The dissipative nature of the process is clear. The figures in the diagram refer to percentile of local exergy destruction in each one of the control volumes.

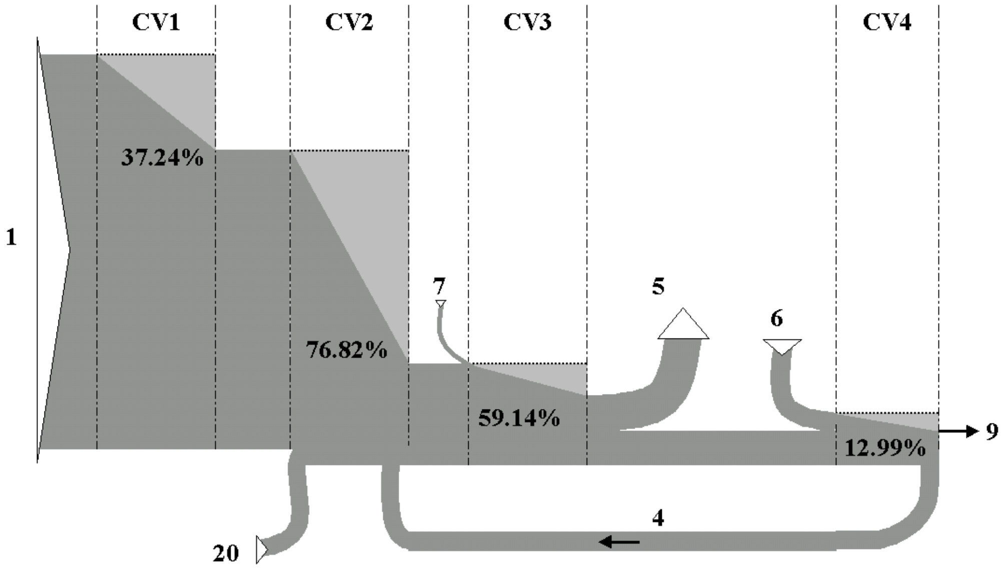

Figure 5. Grassmann type diagram of the “reference” industrial dryer.

5.2 Cogeneration

Results of the simulation of the second alternative, when cogeneration by microturbines is included in the reference plant, are presented and discussed in this sub-section. They are summarized in Table (2).

The overall rational efficiency of the plant is calculated. Now, surplus electricity (flow 22) is also considered a useful effect (product) of the whole plant, while electricity (flow 20) is no longer a needed external resource.

Table 2. Temperature, mass, energy and exergy flows in design condition of the drying plant with cogeneration

flux	description	T °C	kg/s	$\dot{E}$ kW	kW
1	natural gas heater	20.00	2.60	5,823.59	5,317.88
2	combustion gases	1,503.45	2.60	5,604.29	3,337.74
3	drying gases	100.00	81.00	10,743.56	909.73
4	hot gases	39.35	77.47	4,846.95	242.93
5	saturated gases	31.50	82.39	8,610.23	313.10
6	air (6)	19.55	77.47	3,279.68	219.65
7	soybeans (7)	20.00	29.17	1,549.53	3.22
8	soybeans (8)	48.00	27.78	3,439.86	60.39
9	soybeans (9)	24.75	27.78	1,773.68	-
10	microturbine gases	272.00	0.93	338.32	74.00
11	natural gas microturbine	20.00	0.93	561.11	487.46
20	electricity	-	-	66.24	66.24
22	surplus electricity microturbine	-	-	23.76	23.76

The implementation of cogeneration did improve the way energy is utilized in the drying process. Nevertheless the gain is almost negligible. The energy efficiency became 76.99% and the exergy efficiency turned out to be 5.59 %.

The new Grassmann chart of Fig. (6) shows the exergy contribution of the microturbines to the drying plant, namely, electricity and exhaust gasses. The total expenditure of natural gas is a little lower (2,73 kg/s).

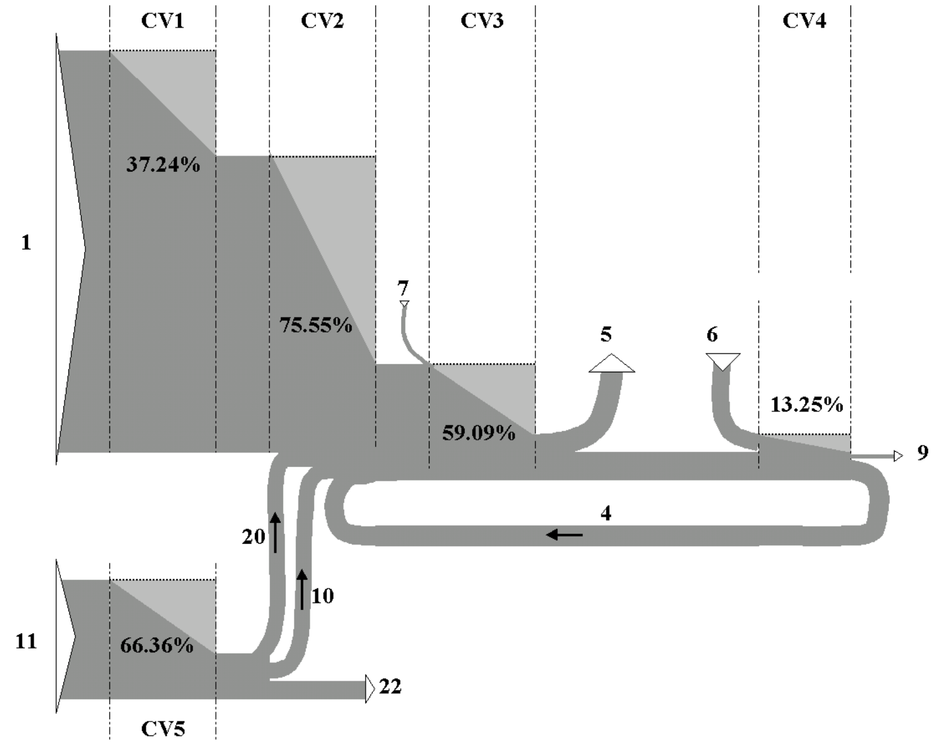

Figure 6. Grassmann type diagram of the soybeans drying plant with cogeneration (natural gas).

5.3 Trigeneration

The last energetic alternative studied in this paper is the drying plant with trigeneration, as described earlier in section 3.3. The results produced by the numerical simulation are summarized in Table (3). There is now three equipments making use of natural gas as fuel. There is a new additional useful effect of the whole plant, namely, surplus electricity of the fuel cell. The overall exergetic rational efficiency improved near 50% when compared to the reference plant performance: it was raised to 7.92%. Trigeneration was even more interesting because while it considerably increased exergetic efficiency it brought the energy performance down to 73.02 %.

Table 3. Temperature, mass, energy and exergy flows in design condition of the drying plant with trigeneration

flux	description	T ºC	$\dot{m}$ kg/s	$\dot{E}$ kW	$\dot{E}_x$ kW
1	natural gas heater	20.00	2.73	6,100.17	5,570.45
2	combustion gases	1,503.45	2.73	5,870.46	3,496.27
3	drying gases	100.00	81.72	10,862.17	919.02
4	hot gases	39.35	78.07	4,884.53	244.81
5	saturated gases	32.05	83.11	8,724.93	317.85
6	air (6)	17.15	78.07	3,113.79	225.62
7	soybeans (7)	20.00	29.17	1,549.53	3.22
8	soybeans (8)	48.00	27.78	3,439.86	60.39
9	soybeans (9)	21.90	27.78	1,569.43	1.15
10	microturbine gases	272.00	0.93	338.32	74.00
11	natural gas microturbine	20.00	0.93	561.11	487.46
12	cooling air	17.15	78.07	3,113.79	225.62
13	air (13)	20.00	78.07	3,341.02	220.73
14	water (14)	14.00	8.33	488.09	6.67
15	water (15)	7.20	8.33	251.02	17.46
16	water (16)	88.00	9.52	3,506.30	250.27
17	water (17)	82.99	9.52	3,306.64	212.05
18	water (18)	83.50	9.52	3,327.00	215.80
19	natural gas fuel cell	20.00	2.63	703.64	557.03
20	electricity	-	-	66.24	66.24
21	surplus electricity fuel cell	-	-	133.76	133.76
22	surplus electricity microturbine	-	-	90.00	90.00
23	heat (23)	25.00	-	382.60	-
24	heat (24)	50.00	-	271.27	-

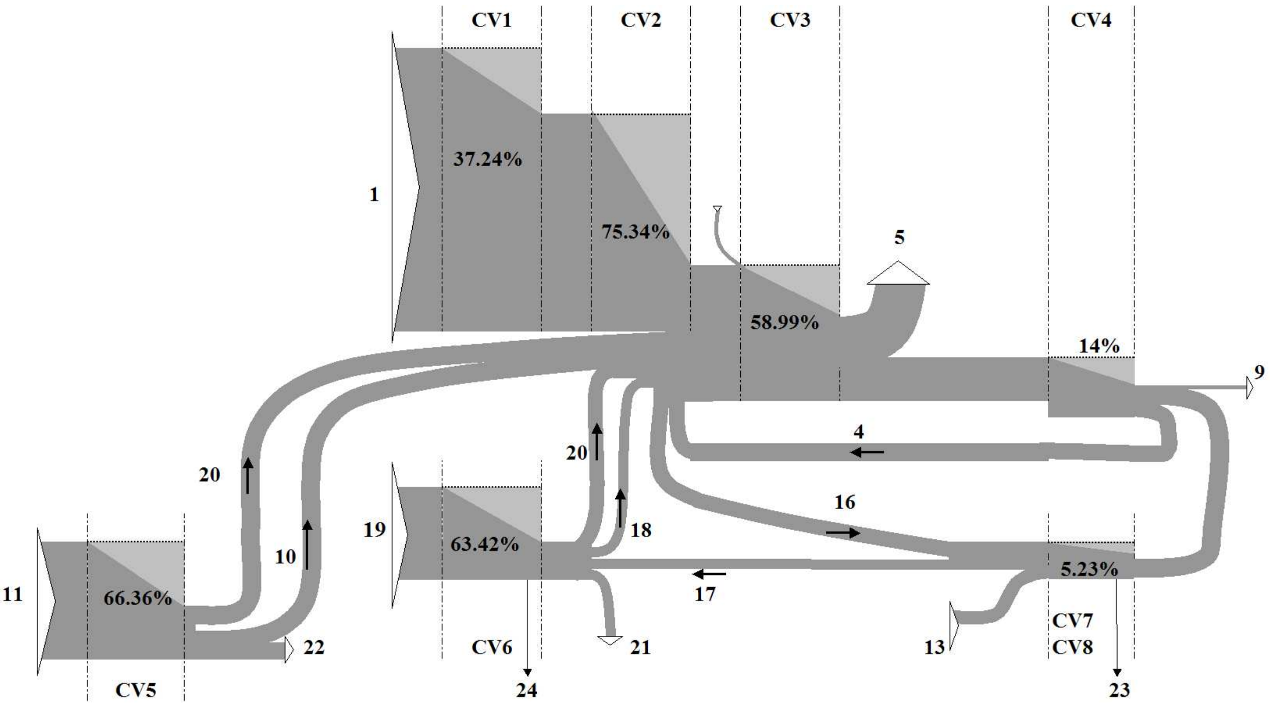

Figure 7. Grassmann type diagram of the soybeans drying plant with trigeneration (natural gas).

The Grassmann chart of Fig. (7) shows the contribution of the fuel cell and of the microturbines to main drying plant. It also shows that even though fuel cell is known to be very efficient, that does not happen when hydrogen is generated at the spot.

6. Results and Discussion

The low exergetic efficiency of the reference drying plant show that indeed those plants are dissipatives - that cannot be directly concluded by the energetic efficiency since it is around 70%.

Grassmann chart of Fig. (5) show that most of the exergy destruction take place at the mixing chamber, not at the furnace.

In the cogeneration plant, the use of exhaust gasses of the microturbines in the drying air mass did improve the overall performance of the plant. Surplus electricity was also generated, and yet little efficiency gain was observed.

The plant with trigeneration showed the best exergetic performance and the poorest energetic performance. The exergetic efficiency was almost 8%. That shows that the dissipative nature of the process still prevails.

7. Conclusions

This paper presents a complete thermodynamic analysis of a conventional soybeans drying plant. Energy and exergy inventories were carried out for a “reference” drying plant that matches most of Brazilian plants. The exergetic performances of such plants are very low and for that reason two energetic alternatives were devised: one alternative with cogeneration by microturbines and trigeneration by an assembly of fuel cell and absorption chiller.

A mathematical model was devised to simulate the energy conversion processes in the plants. A computer code was implemented. Numerical simulations provided results for mass, energy and exergy balance, and rate of irreversibilities as well. The results were summarized in tables and Grassmann type charts.

The main conclusions are that those plants are energy intensive and very inefficient in regard to the Second Law of Thermodynamics. The conventional plant and the two alternatives present a very dissipative behavior. Such characteristic is not shown by conventional energy analyses, which show that exergy must be considered in any effort to improve the way energy is used to dry grains.

The present analysis also showed that most of the exergy destruction takes place in the mixing chamber. Therefore that part of the equipment studied further.

One qualitative conclusion that can be drawn from the exergetic analysis is that there is a great mismatch between energy source and the needs of the process. Therefore, high levels of cogeneration or perhaps biomass gasses that yield moderate flame temperature should be investigated.

The next step in the quest for solutions is to introduce the tools of Thermoeconomics.

8. Acknowledgment

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