MATHEMATICAL MODELING OF INDUSTRIAL SOYBEANS DRYERS WITH COGENERATION OR TRIGENERATION

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Abstract. *This paper introduces a mathematical model as a tool for studying the operation of industrial soybeans dryers. In order to optimize energetically and economically the functioning of such plants, there are studied various configurations for industrial dryers with cogeneration or trigeneration. The analysis of performances for different dryers is donee by comparing the results of numerical simulations with those of a 100 t/h continuous mixed-flow direct-fired "reference" column dryer with forced-air drying and cooling, that basically contains four control volumes: (1) the heater, (2) the mixture chamber where the combustion gas from heater mixtures with the air leaving the cooling chamber, to increase the energy efficiency, (3) the cooling chamber where the soybeans is cooled to reduce the over drying, and (4) the drying "zone" where some of the moisture from grain is effectively removed. The manufacturer's technical data for the "reference" dryer are characteristic for the majority of industrial soybeans dryers in Paraná, Brazil. Results based on the mathematical model presented in this paper are further employed to develop a rational analysis of economical and technical feasibility of natural gas, as an alternative combustible for agricultural industries.*

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

1. Introduction

Glycine max L. Merrill, well known as soybeans, originates in the Extreme-Orient. English and Japanese or Chinese emigrants brought it into some regions all over the world. Early in the twenty-century, soybeans begun to spread into Brazil, but only during the low harvests seventies in USA and Russia, started its real expansion into the Brazilian territory. Very soon, the Brazilian production overcame those of China, the first soybeans producer of the world until then.

Soybeans production in Brazil almost doubles during the last decade, increasing from 27 to 49 million tons/year. The soybeans-related agricultural industries that process grains, bran and oil, having a billionaire annul incoming, are actually ones of the most profitable economical activities, responsible for 15% of the total amount of Brazilian exportation in 2003. According to the Brazilian National Confederation of Industry, more than 50% of the 2003 soybeans harvest will be pre-processed by the Brazilian industry before setting it up for sale on international markets. This will dramatically increase the need for new investments in more efficient plants and more productive technologies. In terms of potential of consumption, the 2003 soybeans harvest drying represents a minimum of 6,500 TJ of thermal energy to be commercialized by the Brazilian energy market.

Therefore, many researchers are concerned with a better understanding of processes into industrial grains dryers in order to optimize energetically and economically their functioning, to define the feasibleness of cogeneration or trigeneration, and to evaluate the economical and technical feasibility of natural gas for agricultural industries. Soponronnarit et all (2001) developed a mathematical model to study the fluidized bed Diesel fuelled drying soybeans process. Results of numerical simulation performed by them show that the total primary energy consumption was 6.8 MJ/kg water evaporated and the drying cost was US$ 0.06/kg water evaporated. Recent results based on performances monitoring in industrial grain dryers during their operation have been presented by Chen et all (2002) and then compared against ISO standards. The relatively large number of authors addressing the challenging problem of automatic control of drying process (Zhang and Litchfield, 1994, Arinse et all, 1994, Liu e Bakker-Arkema, 2001) demonstrates the importance of increasing the quality of drying process and the energetic efficiency.

The purpose of this paper is to develop an isobaric mathematical model to study the whole operation of industrial soybeans dryers. While almost all of the existing mathematical models for grain dryers exclusively focus on the dehydration process, this paper presents a model that accounts for processes occurring into the four control volumes of an industrial dryer: (1) the heater, (2) the mixture chamber where the combustion gas from heater mixtures with the air leaving the cooling chamber, to increase the energy efficiency, (3) the cooling chamber where the soybeans is cooled to avoid the over drying, and (4) the drying "zone" where some of the moisture from grain is effectively removed. In order to optimize energetically and economically the functioning of such plants, there are studied various configurations for industrial dryers with cogeneration or trigeneration. Results based on the mathematical model presented in this paper are employed to develop a rational analysis of economical and technical feasibility of natural gas, as an alternative combustible for agricultural industries.

2. Description of the soybeans "reference" dryer functioning

Analysis of performances for different dryers has been performed by comparing the results of numerical simulations with those of a 100 t/h continuous mixed-flow direct-fired "reference" column dryer with forced-air drying and cooling. The manufacturer's technical data for the "reference" dryer are characteristic for the majority of industrial soybeans dryers in Paraná, Brazil. As shown in Fig. (1) the "reference" dryer basically contains four control volumes: (1) the heater, (2) the mixture chamber, (3) the cooling chamber, and (4) the drying "zone".

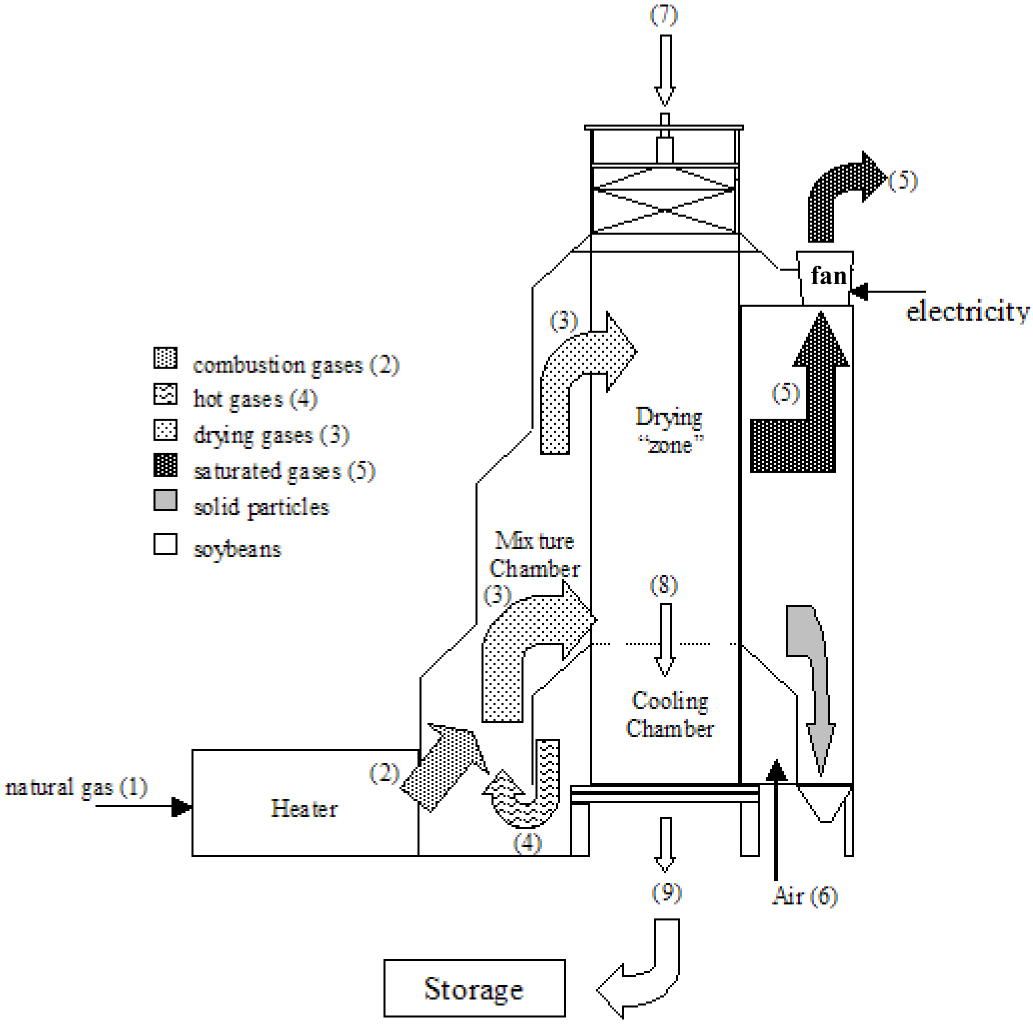

Figure 1. Schematic view of the "reference" industrial dryer.

The drying "zone", where the moisture from grain is effectively removed, is crossed along vertical direction by a 100 t/h wet soybeans flow and horizontally by a hot homogenous gas mixture flow of air and combustion gas. The "reference" dryer reduces the moisture content of soybeans from $c_{H_2O_{liq},7} = 18\%$ at the entrance, to $c_{H_2O_{liq},9} = 13\%$ when soybeans leave the drying zone, while the soybeans temperature increases from 20^0C to 48^0C. During the process of moisture removal some of the internal energy of the hot low relative humidity gas mixture, that enters the drying "zone" at 100^0C, is used to evaporate the liquid water soybeans' content.

To avoid that dry soybeans naturally pick up moisture from the atmosphere during the storage, it is cooled down into the cooling chamber before leaving the dryer. Some of the internal energy of soybeans, removed during the cooling, gradually enters the atmospheric airflow (the heat sink) increasing its temperature before it enters the mixture chamber. Next, the pre-heated atmospheric airflow leaving the cooling chamber is conducted to the mixture chamber. Here, it mixtures with the hot combustion gases from the heater, producing the low relative humidity gas mixture for the drying process. Regeneration of heat removed from the soybeans during its cooling contributes for the energetic efficiency increase.

3. Simulation model development

Assuming steady-state operation of the soybeans "reference" dryer, equations needed to calculate temperature and the flow rates at entries and exit ports are the mass and mole balances and the energy balance (the first Law of

Thermodynamics) for each one of the four control volumes. Figure (2) shows the mass flow rates ($\dot{m}_{soybeans}$) and molar flow rates ($\dot{n}_i$, i = CH_4, O_2, N_2, H_2O_{gas}, H_2O_{liq}, CO_2) to be determined.

The pressure drop in the dryer is neglected.

In this study the natural gas is assumed to be methane (CH_4) and to burn completely (all the carbon appears as CO_2 and all hydrogen appears as H_2O in the products) according to the following chemical reaction:

$$
\begin{aligned}
& CH_4 + 2\lambda_f O_2 + 7{,}52\lambda_f N_2 + 9{,}52\lambda_f \frac{\varphi_1 p_{sat}(T_1)}{p_1 - \varphi_1 p_{sat}(T_1)} H_2O \rightarrow \\
& CO_2 + \left[2 + 9{,}52\lambda_f \frac{\varphi_1 p_{sat}(T_1)}{p_1 - \varphi_1 p_{sat}(T_1)} \right] H_2O + 2(\lambda_f - 1)O_2 + 7{,}52\lambda_f N_2
\end{aligned} \tag{1}
$$

In Eq. (1) $\lambda_f - 1 \geq 0$ represents the excess air, $\varphi_1 = \varphi_0$ is the relative humidity of atmospheric air, $p_1 = p_0$ is the atmospheric pressure and $p_{sat}(T_1)$ gives the saturation pressure of water at $T_1 = T_0$ (Dong and Lienhard, 1986).

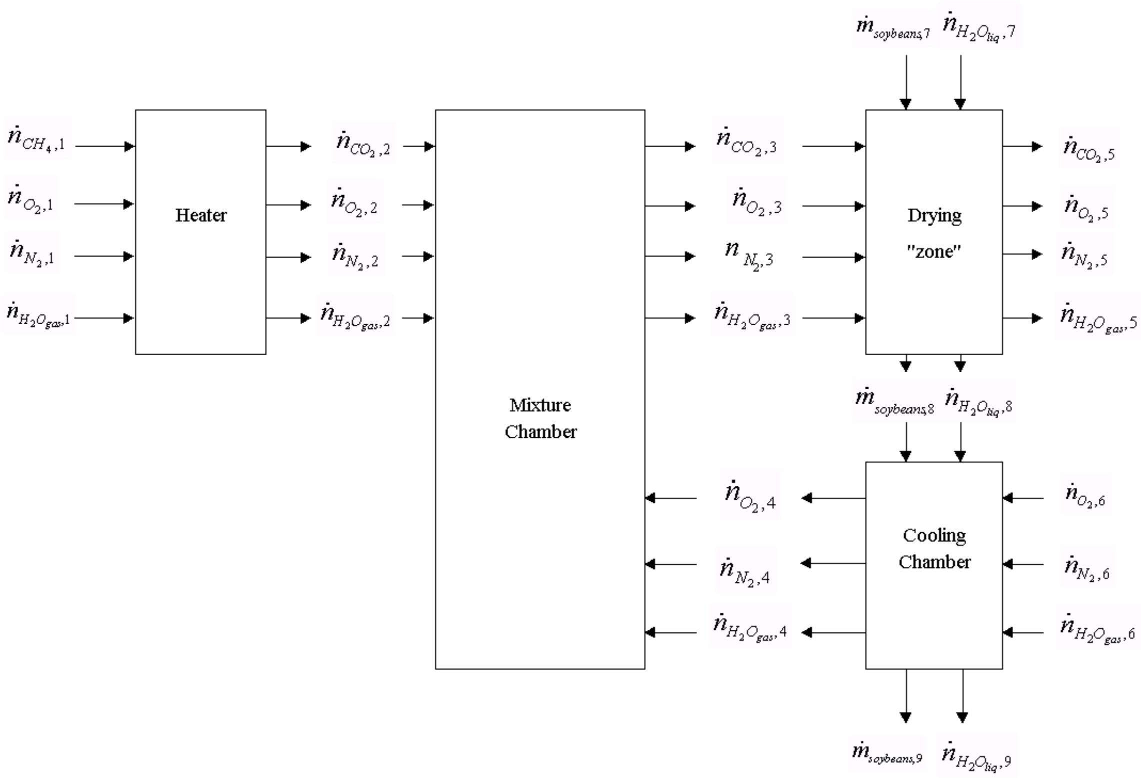

Figure 2. Mass and molar flow rates at entries and exit ports of the four control volumes of "reference" industrial dryer.

3.1. Mathematical modeling of soybeans "reference" dryer

3.1.1 Heater

- Mole balance:

$$\dot{n}_{O_2,1} = 2\lambda_f \dot{n}_{CH_4,1} \tag{2a}$$

$$\dot{n}_{H_2O,1} = 9{,}52\lambda_f \frac{\varphi_1 p_{sat}(T_1)}{p_1 - \varphi_1 p_{sat}(T_1)} \dot{n}_{CH_4,1} \tag{2b}$$

$$\dot{n}_{N_2,1} = 7{,}52\lambda_f \dot{n}_{CH_4,1} \tag{2c}$$

$$\dot{n}_{CO_2,2} = \dot{n}_{CH_4,1} = c_1 \dot{n}_{CH_4,1} \tag{2d}$$

$$\dot{n}_{H_2O,2} = \left[2 + 9{,}52\lambda_f \frac{\varphi_1 p_{sat}(T_1)}{p_1 - \varphi_1 p_{sat}(T_1)}\right]\dot{n}_{CH_4,1} = c_2 \dot{n}_{CH_4,1} \tag{2e}$$

$$\dot{n}_{O_2,2} = 2(\lambda_f - 1)\dot{n}_{CH_4,1} = c_3 \dot{n}_{CH_4,1} \tag{2f}$$

$$\dot{n}_{N_2,2} = 7{,}52\lambda_f \dot{n}_{CH_4,1} = c_4 \dot{n}_{CH_4,1} \tag{2g}$$

where $\dot{n}_{CH_4,1}$ represents the dryer's consumption of natural gas.

- Energy balance:

$$\begin{aligned} &\dot{Q}_{vc,1} + \dot{n}_{CH_4,1}(\overline{h}_f^0 + \Delta\overline{h})_{CH_4,1} + \dot{n}_{O_2,1}(\Delta\overline{h})_{O_2,1} + \dot{n}_{N_2,1}(\Delta\overline{h})_{N_2,1} + \dot{n}_{H_2O,1}(\overline{h}_f^0 + \Delta\overline{h})_{H_2O,1} = \\ &\dot{n}_{CO_2,2}(\overline{h}_f^0 + \Delta\overline{h})_{CO_2,2} + \dot{n}_{H_2O,2}(\overline{h}_f^0 + \Delta\overline{h})_{H_2O,2} + \dot{n}_{O_2,2}(\Delta\overline{h})_{O_2,2} + \dot{n}_{N_2,2}(\Delta\overline{h})_{N_2,2} \end{aligned} \tag{3}$$

where: $-\dot{Q}_{vc,1}/(\dot{n}_{CH_4,1}HHV) = \varepsilon = 0\ldots0{,}15$ represents the heat losses, $\overline{h}_f^0$ is the enthalpy of formation, and $\Delta\overline{h}$ is the molar enthalpy variation between the reference state and thermodynamic states at the entries or exit ports of the control volume.

3.1.2 Mixture chamber

- Mole balance:

$$\dot{n}_{CO_2,3} = \dot{n}_{CO_2,2} \tag{4a}$$

$$\dot{n}_{H_2O_{gas},3} = \dot{n}_{H_2O_{gas},2} + \dot{n}_{H_2O_{gas},4} \tag{4b}$$

$$\dot{n}_{O_2,3} = \dot{n}_{O_2,2} + \dot{n}_{O_2,4} \tag{4c}$$

$$\dot{n}_{N_2,3} = \dot{n}_{N_2,2} + \dot{n}_{N_2,4}\,. \tag{4d}$$

- Energy balance:

$$\begin{aligned} &\eta_m(\dot{n}_{CO_2,2}\Delta\overline{h}_{CO_2,2} + \dot{n}_{H_2O_{gas},2}\Delta\overline{h}_{H_2O_{gas},2} + \dot{n}_{O_2,2}\Delta\overline{h}_{O_2,2} + \dot{n}_{N_2,2}\Delta\overline{h}_{N_2 2} + \dot{n}_{O_2,4}\Delta\overline{h}_{O_2,4} + \dot{n}_{N_2,4}\Delta\overline{h}_{N_2,4} + \\ &+ \dot{n}_{H_2O_{gas},4}\Delta\overline{h}_{H_2O_{gas},4}) = \dot{n}_{CO_2,3}\Delta\overline{h}_{CO_2,3} + \dot{n}_{H_2O_{gas},3}\Delta\overline{h}_{H_2O_{gas},3} + \dot{n}_{O_2,3}\Delta\overline{h}_{O_2,3} + \dot{n}_{N_2,3}\Delta\overline{h}_{N_2,3} \end{aligned} \tag{5}$$

with 1 - η_m indicating the losses of thermal energy in the mixture chamber.

3.1.3 Cooling chamber

- Mass and mole balance (assuming the moisture removal occurs exclusively into the drying "zone"):

$$\dot{m}_{soybeans,8} = \dot{m}_{soybeans,9} \tag{6a}$$

$$\dot{n}_{H_2O_{liq},8} = \dot{n}_{H_2O_{liq},9} \tag{6b}$$

$$\dot{n}_{O_2,6} = \dot{n}_{O_2,4} \tag{6c}$$

$$\dot{n}_{N_2,6} = \dot{n}_{N_2,4} = 3{,}76\dot{n}_{O_2,6} \tag{6d}$$

$$\dot{n}_{H_2O_{gas},6} = \dot{n}_{H_2O_{gas},4} = 4{,}76\frac{\varphi_6 psat(T_6)}{p_6 - \varphi_6 psat(T_6)}\dot{n}_{O_2,6} \tag{6e}$$

where $\varphi_6 = \varphi_1$ e $T_6 = T_1$.

- Energy balance:

$$\eta_r(\dot{m}_{soybeans,8}\Delta h_{soja,8} + \dot{n}_{H_2O_{liq},8}\Delta\bar{h}_{H_2O_{liq},8} - \dot{m}_{soybeans,9}\Delta h_{soja,9} - \dot{n}_{H_2O_{liq},9}\Delta\bar{h}_{H_2O_{liq},9}) =$$
$$\dot{n}_{O_2,4}\Delta\bar{h}_{O_2,4} + \dot{n}_{N_2,4}\Delta\bar{h}_{N_2,4} + \dot{n}_{H_2O_{gas},4}\Delta\bar{h}_{H_2O_{gas},4} - \dot{n}_{O_2,6}\Delta\bar{h}_{O_2,6} - \dot{n}_{N_2,6}\Delta\bar{h}_{N_2,6} - \dot{n}_{H_2O_{gas},6}\Delta\bar{h}_{H_2O_{gas},6} \quad (7)$$

where 1 - η_r indicates the thermal inefficiency of the cooling chamber.

3.1.4 Drying “zone”

- Mass and mole balance (assuming the moisture removal occurs exclusively into the drying “zone”):

$$\dot{m}_{soybeans,7} = \dot{m}_{soybeans,8} \quad (8a)$$

$$\dot{n}_{CO_2,5} = \dot{n}_{CO_2,3} \quad (8b)$$

$$\dot{n}_{H_2O_{gas},5} = \dot{n}_{H_2O_{gas},3} + \dot{n}_{H_2O_{liq},7} - \dot{n}_{H_2O_{liq},8} \quad (8c)$$

$$\dot{n}_{O_2,5} = \dot{n}_{O_2,3} \quad (8d)$$

$$\dot{n}_{N_2,5} = \dot{n}_{N_2,3} \quad (8e)$$

- Energy balance:

$$\eta_s(\dot{m}_{soybeans,7}\Delta h_{soja,7} + \dot{n}_{H_2O_{liq},7}\Delta\bar{h}_{H_2O_{liq},7} + \dot{n}_{CO_2,3}\Delta\bar{h}_{CO_2,3} + \dot{n}_{H_2O_{gas},3}\Delta\bar{h}_{H_2O_{gas},3} + \dot{n}_{O_2,3}\Delta\bar{h}_{O_2,3} + \dot{n}_{N_2,3}\Delta\bar{h}_{N_2,3}) +$$
$$\dot{n}_{H_2O_{liq},7}\bar{h}^0_{f,H_2O_{liq}} + \dot{n}_{CO_2,3}\bar{h}^0_{f,CO_2} + \dot{n}_{H_2O_{gas},3}\bar{h}^0_{f,H_2O_{gas}} =$$
$$\dot{m}_{soybeans,8}\Delta h_{soybeans,8} + \dot{n}_{H_2O_{liq},8}\Delta\bar{h}_{H_2O_{liq},8} + \dot{n}_{CO_2,5}\Delta\bar{h}_{CO_2,5} + \dot{n}_{H_2O_{gas},5}\Delta\bar{h}_{H_2O_{gas},5} + \dot{n}_{O_2,5}\Delta\bar{h}_{O_2,5} + \dot{n}_{N_2,5}\Delta\bar{h}_{N_2,5} +$$
$$\dot{n}_{H_2O_{liq},8}\bar{h}^0_{f,H_2O_{liq}} + \dot{n}_{CO_2,5}\bar{h}^0_{f,CO_2} + \dot{n}_{H_2O_{gas},5}\bar{h}^0_{f,H_2O_{gas}} \quad (9)$$

Thermal efficiency of the drying “zone”, η_s, accounts only for losses related to the enthalpy variations, $\Delta h_{soybeans}$ and $\Delta\bar{h}_i$ ($i = O_2, N_2, H_2O_{gas}, H_2O_{liq}, CO_2$).

3.1.5 Numerical procedure

Equations (2) - (9) represent the mathematical model to study the soybeans “reference” dryer functioning. In Fig. (3) it is shown the flow chart of the numerical procedure employed to solve this parametric nonlinear algebraic system.

Based on the heater energy balance in Eq. (3), the first step determines the temperature of hot combustion gases leaving the heater, $T_2 = T_2(T_0, \varphi_0, \lambda_f, \dot{Q}_{vc,1})$.

Then, substituting Eqs. (6a) - (6e) into Eq. (7) and guessing a first value of T_4^*, the oxygen mole flow rate at the entrance of the cooling chamber, $\dot{n}_{O_2,6}$, is given by:

$$\dot{n}_{O_2,6} = \frac{\eta_r[\dot{m}_{soja,9}(\Delta h_{soja,8} - \Delta h_{soja,9}) + \dot{n}_{H_2O_{liq},9}(\Delta\bar{h}_{H_2O_{liq},8} - \Delta\bar{h}_{H_2O_{liq},9})]}{(\Delta\bar{h}_{O_2,4} - \Delta\bar{h}_{O_2,6}) + 3{,}76(\Delta\bar{h}_{N_2,4} - \Delta\bar{h}_{N_2,6}) + 4{,}76\dfrac{\varphi_6 psat(T_6)(\Delta\bar{h}_{H_2O_{gas},4} - \Delta\bar{h}_{H_2O_{gas},6})}{p_6 - \varphi_6 psat(T_6)}} \quad (10)$$

Next, combining Eqs. (2a) – (2g), (4a) – (4d) and (5) yields the mole flow rate of natural gas at the entrance of heater, $\dot{n}_{CH_4,1}$:

$$\dot{n}_{CH_4,1} = [\dot{n}_{O_2,4}(\Delta\bar{h}_{O_2,3} - \eta_m\Delta\bar{h}_{O_2,4}) + n_{N_2,4}(\Delta\bar{h}_{N_2,3} - \eta_m\Delta\bar{h}_{N_2,4}) + n_{H_2O_{gas},4}(\Delta\bar{h}_{H_2O_{gas},3} - \eta_m\Delta\bar{h}_{H_2O_{gas},4})]/$$

$$[c_1(\eta_m \Delta \bar{h}_{CO_2,2} - \Delta h_{CO_2,3}) + c_2(\eta_m \Delta \bar{h}_{H_2O_{gas},2} - \Delta h_{H_2O_{gas},3}) + c_3(\eta_m \Delta \bar{h}_{O_2,2} - \Delta h_{O_2,3}) + c_4(\eta_m \Delta \bar{h}_{N_2,2} - \Delta h_{N_2,3})] \quad (11)$$

and the mole flow rates, $\dot{n}_{O_2,i}$, $\dot{n}_{N_2,i}$, $\dot{n}_{H_2O_{liq},i}$, $\dot{n}_{H_2O_{gas},i}$, $\dot{n}_{CO_2,i}$.

Temperature T_5 of the saturated gas mixture leaving the drying "zone" is now the only unknown of drying "zone" energy balance in Eq. (9). In the third step, relative humidity φ_5 is also determined by:

$$\varphi_5 = \frac{p_5}{p_{sat}(T_5)} \frac{\dot{n}_{H_2O_{gas},5}}{\dot{n}_{CO_2,5} + \dot{n}_{H_2Ogas,5} + \dot{n}_{O_2,5} + \dot{n}_{N_2,5}} \quad (12)$$

To maximize the dryer's energetic efficiency, the numerical procedure stops when the relative humidity of saturated gas mixture leaving the drying "zone" reaches the ceiling value $\varphi_{5,max} = 100\%$.

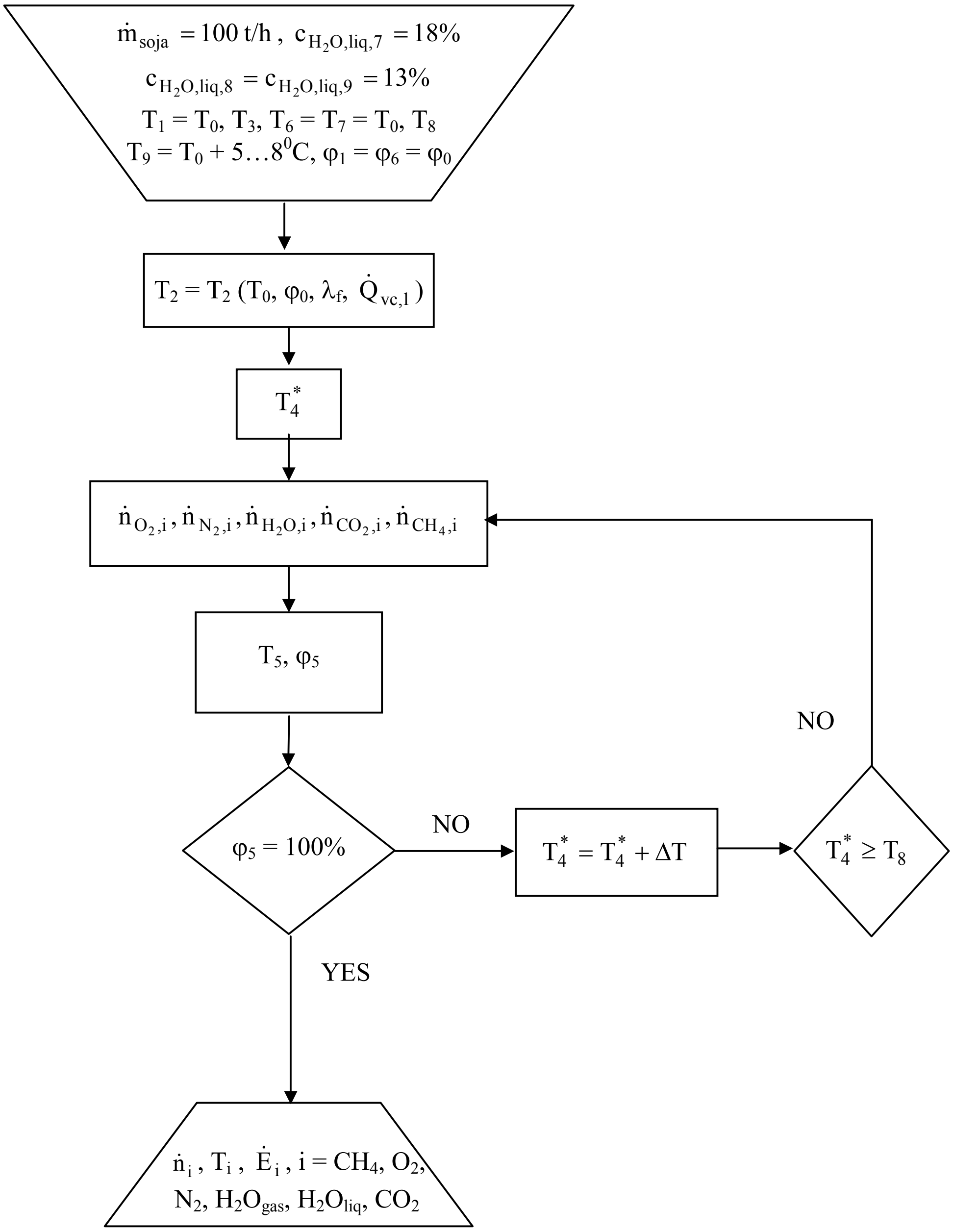

Figure 3. Numerical procedure flow chart.

3.2. Mathematical modeling of soybeans drying cogeneration plants

To study the feasibleness of the natural gas simultaneous generation of electricity and thermal energy for moisture removal, it is considered a soybeans dryer configuration as shown in Fig. (4).

The new physical structure of the drying plant contains a fifth control volume, representing an electrical power generator (e.g., a high-pressure gaseous fuel 330 Capstone Micro Turbine™). To fit the previous mathematical model to study the functioning of soybeans drying cogeneration plants, Eqs. (4) and (5) change as follows:

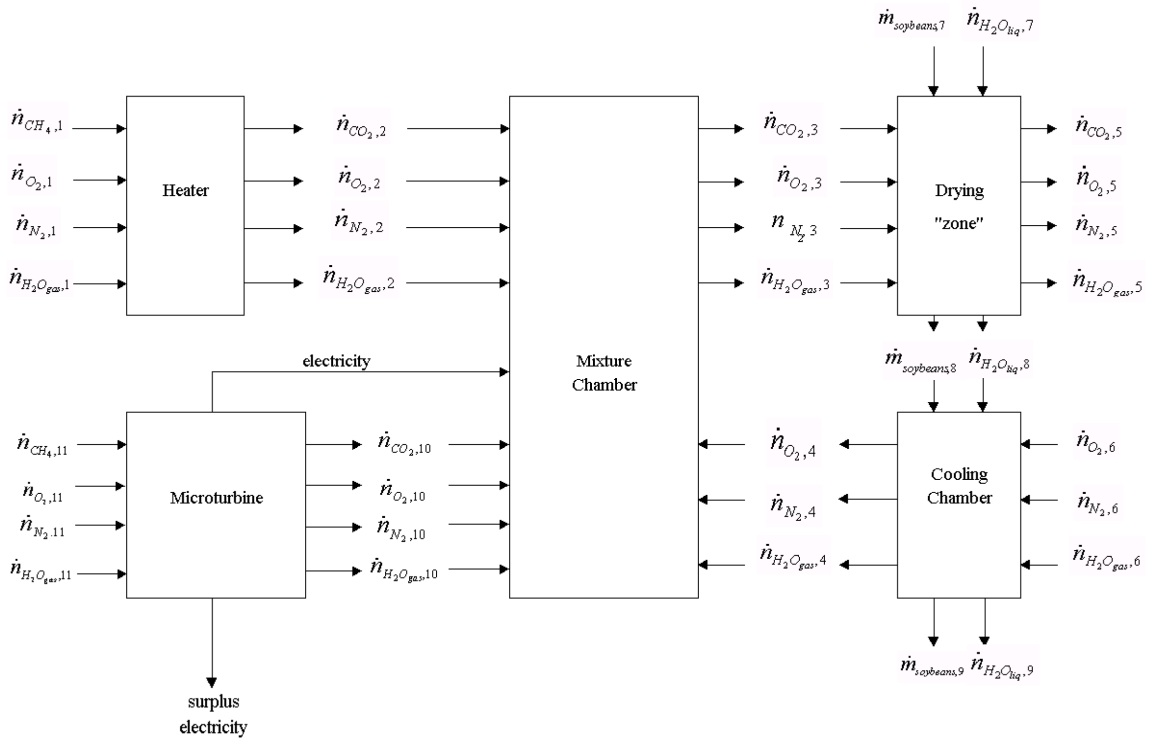

Figure 4. Physical structure of soybeans dryer with natural gas cogeneration.

$$\dot{n}_{CO_2,3} = \dot{n}_{CO_2,2} + \dot{n}_{CO_2,10} \tag{4a'}$$

$$\dot{n}_{H_2O_{gas},3} = \dot{n}_{H_2O_{gas},2} + \dot{n}_{H_2O_{gas},4} + \dot{n}_{H_2O_{gas},10} \tag{4b'}$$

$$\dot{n}_{O_2,3} = \dot{n}_{O_2,2} + \dot{n}_{O_2,4} + \dot{n}_{O_2,10} \tag{4c'}$$

$$\dot{n}_{N_2,3} = \dot{n}_{N_2,2} + \dot{n}_{N_2,4} + \dot{n}_{N_2,10} \tag{4d'}$$

$$\begin{aligned}&\eta_m(\dot{n}_{CO_2,2}\Delta\bar{h}_{CO_2,2} + \dot{n}_{H_2O_{gas},2}\Delta\bar{h}_{H_2O_{gas},2} + \dot{n}_{O_2,2}\Delta\bar{h}_{O_2,2} + \dot{n}_{N_2,2}\Delta\bar{h}_{N_2 2} + \dot{n}_{O_2,4}\Delta\bar{h}_{O_2,4} + \dot{n}_{N_2,4}\Delta\bar{h}_{N_2,4} +\\ &+ \dot{n}_{H_2O_{gas},4}\Delta\bar{h}_{H_2O_{gas},4} + \dot{n}_{CO_2,10}\Delta\bar{h}_{CO_2,10} + \dot{n}_{H_2O_{gas},10}\Delta\bar{h}_{H_2O_{gas},10} + \dot{n}_{O_2,10}\Delta\bar{h}_{O_2,10} + \dot{n}_{N_2,10}\Delta\bar{h}_{N_2,10}) =\\ &\dot{n}_{CO_2,3}\Delta\bar{h}_{CO_2,3} + \dot{n}_{H_2O_{gas},3}\Delta\bar{h}_{H_2O_{gas},3} + \dot{n}_{O_2,3}\Delta\bar{h}_{O_2,3} + \dot{n}_{N_2,3}\Delta\bar{h}_{N_2,3}\end{aligned} \tag{5'}$$

Consumption of the whole cogeneration plant is given by $\dot{n}_{CH_4,1} + \dot{n}_{CH_4,11}$.

3.3. Mathematical modeling of soybeans drying trigeneration plants

Figure (5) shows the physical structure of a grain drying plant that simultaneously generates electricity, thermal energy for moisture removal, and cold air for cooling down the soybeans before it leaves the dryer.

The eight control volumes of this new configuration are: (1) the heater, (2) the mixture chamber, (3) the cooling chamber where the soybeans is cooled to avoid that dry soybeans naturally pick up moisture from the atmosphere during the storage, (4) the drying "zone" where the moisture of grains is effectively removed, (5) an electrical power generator that also produces hot gases for the mixture chamber (e.g., a high-pressure gaseous fuel 330 Capstone Micro Turbine™), (6) a fuel cell to produce electricity and hot water (e.g., a ONSI Corporation PC25™C Fuel Cell), (7) an absorption chiller (e.g., a Yazaki Energy Systems, Inc WFC-10 water fired chiller), and (8) a heat exchanger to cool down the atmospheric air that enters the cooling chamber.

Temperature T_5 of the cold air entering the dryer's cooling chamber is now determined based on the heat exchanger energy balance:

$$\eta_{he}(\dot{n}_{O_2,13}\Delta\bar{h}_{O_2,13} + \dot{n}_{N_2,13}\Delta\bar{h}_{N_2,13} + \dot{n}_{H_2O_{gas},13}\Delta\bar{h}_{H_2O_{gas},13} + \dot{n}_{H_2O_{liq},15}\Delta\bar{h}_{H_2O_{liq},15}) =$$
$$\dot{n}_{O_2,6}\Delta\bar{h}_{O_2,6} + \dot{n}_{N_2,6}\Delta\bar{h}_{N_2,6} + \dot{n}_{H_2O_{gas},6}\Delta\bar{h}_{H_2O_{gas},6} + \dot{n}_{H_2O_{liq},14}\Delta\bar{h}_{H_2O_{liq},14} \qquad (13)$$

where η_{he} represents the heat exchanger thermal efficiency.

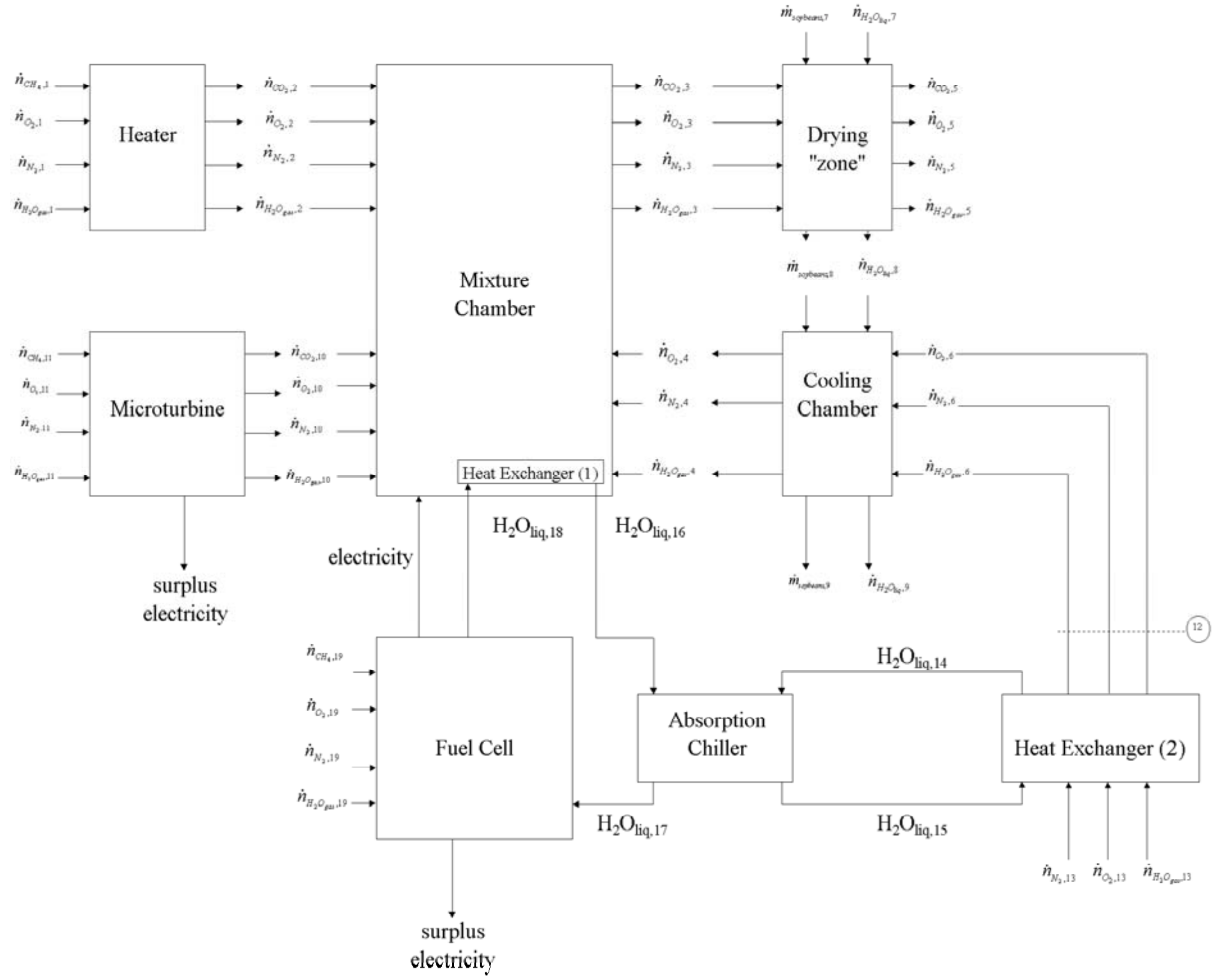

Figure 5. Physical structure of soybeans dryer with natural gas trigeneration.

To study the functioning of soybeans drying trigeneration plant, the algebraic expression of the mixture chamber's energy balance is:

$$\eta_m(\dot{n}_{CO_2,2}\Delta\bar{h}_{CO_2,2} + \dot{n}_{H_2O_{gas},2}\Delta\bar{h}_{H_2O_{gas},2} + \dot{n}_{O_2,2}\Delta\bar{h}_{O_2,2} + \dot{n}_{N_2,2}\Delta\bar{h}_{N_2 2} +$$
$$+ \dot{n}_{O_2,4}\Delta\bar{h}_{O_2,4} + \dot{n}_{N_2,4}\Delta\bar{h}_{N_2,4} + \dot{n}_{H_2O_{gas},4}\Delta\bar{h}_{H_2O_{gas},4} + \dot{n}_{CO_2,10}\Delta\bar{h}_{CO_2,10} +$$
$$+ \dot{n}_{H_2O_{gas},10}\Delta\bar{h}_{H_2O_{gas},10} + \dot{n}_{O_2,10}\Delta\bar{h}_{O_2,10} + \dot{n}_{N_2,10}\Delta\bar{h}_{N_2,10} + \dot{n}_{H_2O_{liq},18}\Delta\bar{h}_{H_2O_{liq},18}) =$$
$$\dot{n}_{CO_2,3}\Delta\bar{h}_{CO_2,3} + \dot{n}_{H_2O_{gas},3}\Delta\bar{h}_{H_2O_{gas},3} + \dot{n}_{O_2,3}\Delta\bar{h}_{O_2,3} + \dot{n}_{N_2,3}\Delta\bar{h}_{N_2,3} + \dot{n}_{H_2O_{liq},16}\Delta\bar{h}_{H_2O_{liq},16} \qquad (14)$$

Consumption of the whole trigenerating plant is given by $\dot{n}_{CH_4,1} + \dot{n}_{CH_4,11} + \dot{n}_{CH_4,19}$.

4. Results

Tables (1) - (3) show the results of numerical simulation for various drying plants functioning, with $c_{H_2O_{liq},7}$ = 18%, $c_{H_2O_{liq},9}$ = 13%, φ_0 = 60%, ε = 0, $\eta_m = \eta_r = \eta_s$ = 100%.

Table 1. Computational results for the “reference” industrial dryer (φ_5 = 99.5%).

No.	Flows	T	$\dot{m}$	Mole flow rates (kmol/h)						$\dot{E}$
		°C	kg/s	$\dot{n}_{CO_2}$	$\dot{n}_{O_2}$	$\dot{n}_{N_2}$	$\dot{n}_{CH_4}$	$\dot{n}_{H_2O_{liq}}$	$\dot{n}_{H_2O_{gas}}$	kW
1	Natural gas	**20.0**	2.87	0.0	71.6	269.1	25.6	0.0	4.9	6,449.9
2	Combustion gas	1,573.5	2.87	25.6	20.5	269.1	0.0	0.0	56.1	6,449.9
3	Heated gas	**100.0**	89.6	25.6	2,274.5	8,744.4	0.0	0.0	211.4	11,823.3
4	Hot air	38.6	86.7	0.0	2,254.1	8,475.3	0.0	0.0	155.3	5,361.4
5	Saturated hot gas	32.5	91.3	25.6	2,274.5	8,744.4	0.0	0.0	550.1	9,958.5
6	Atmospheric air	**20.0**	86.7	0.0	2,254.1	8,475.3	0.0	0.0	155.3	3,713.1
7	Wet soybeans	**20.0**	29.5	0.0	0.0	0.0	0.0	1,061.0	0.0	1,575.0
8	Dried hot soybeans	**48.0**	27.8	0.0	0.0	0.0	0.0	722.2	0.0	3,439.8
9	Dried cooled soybeans	**25.0**	27.8	0.0	0.0	0.0	0.0	722.2	0.0	1,791.5

Table 2. Computational results for the cogeneration dryer (φ_5 = 100%).

No.	Flows	T	$\dot{m}$	Mole flow rates (kmol/h)						$\dot{E}$
		°C	kg/s	$\dot{n}_{CO_2}$	$\dot{n}_{O_2}$	$\dot{n}_{N_2}$	$\dot{n}_{CH_4}$	$\dot{n}_{H_2O_{liq}}$	$\dot{n}_{H_2O_{gas}}$	kW
1	Natural gas	**20.0**	2.74	0.0	68.4	257.1	24.4	0.0	4.7	6,160.9
2	Combustion gas	1,573.5	2.74	24.4	19.5	257.1	0.0	0.0	53.5	6,160.9
3	Heated gas	**100.0**	89.5	26.5	2,269.2	8,731.6	0.0	0.0	213.1	11,832.6
4	Hot air	38.8	85.8	0.0	2,230.1	8,385.1	0.0	0.0	153.7	5,321.8
5	Saturated hot gas	32.4	91.2	26.5	2,269.2	8,731.6	0.0	0.0	551.9	9,967.7
6	Atmospheric air	**20.0**	85.8	0.0	2,230.1	8,385.1	0.0	0.0	153.7	3,673.6
7	Wet soybeans	**20.0**	29.5	0.0	0.0	0.0	0.0	1,061.0	0.0	1,575.0
8	Dried hot soybeans	**48.0**	27.8	0.0	0.0	0.0	0.0	722.2	0.0	3,439.8
9	Dried cooled soybeans	**25.0**	27.8	0.0	0.0	0.0	0.0	722.2	0.0	1,791.5
10	Combustion gas	**272.0**	**0.93**	**2.1**	**19.6**	**89.5**	**0.0**	**0.0**	**0.0**	**338.4**
11	Natural gas	**20.0**	**0.93**	**0.0**	**23.8**	**89.5**	**2.1**	**0.0**	**1.6**	**564.3**

Table 3. Computational results for the trigeneration dryer (φ_5 = 99.5%).

No.	Flows s	T	$\dot{m}$	Mole flow rates (kmol/h)						$\dot{E}$
		°C	kg/s	$\dot{n}_{CO_2}$	$\dot{n}_{O_2}$	$\dot{n}_{N_2}$	$\dot{n}_{CH_4}$	$\dot{n}_{H_2O_{liq}}$	$\dot{n}_{H_2O_{gas}}$	kW
1	Natural gas	**20.00**	2.73	-	68.02	255.77	24.29	-	4.69	6,100.17
2	Combustion gas	1,503.45	2.73	24.29	19.44	255.77	-	-	53.28	5,870.46
3	Heated gas	**100.00**	81.72	26.41	2,068.00	7,974.30	-	-	198.97	10,862.17
4	Hot air	39.35	78.07	-	2,029.00	7,629.04	-	-	139.82	4,884.53
5	Saturated hot gas	32.05	83.11	26.41	2,068.00	7,974.30	-	-	476.74	8,724.93
6	Cooled air	17.15	78.07	-	2,029.00	7,629.04	-	-	139.82	3,113.79
7	Wet soybeans	**20.00**	29.17	-	-	-	-	1,000.00	-	1,549.53
8	Dried hot soybeans	**48.00**	27.78	-	-	-	-	722.22	-	3,439.86
9	Dried cooled soybeans	21.90	27.78	-	-	-	-	722.22	-	1,569.43
10	Combustion gas	**272.00**	0.93	2.12	19.57	89.49	-	-	5.88	338.32
11	Natural gas	**20.00**	0.93	-	23.80	89.49	2.12	-	1.64	561.11
12	Cooled air	17.15	78.07	-	2,029.00	7,629.04	-	-	139.82	3,113.79
13	Atmospheric air	**20.00**	78.07	-	2,029.00	7,629.04	-	-	139.82	3,341.02
14	Heated water	**14.00**	8.33	-	-	-	-	1,666.00	-	488.09
15	Cooled water	**7.20**	8.33	-	-	-	-	1,666.00	-	251.02
16	Heated water	**88.00**	9.52	-	-	-	-	1,904.00	-	3,506.30
17	Cooled water	**82.99**	9.52	-	-	-	-	1,904.00	-	3,306.64
18	Heated water	**83.50**	9.52	-	-	-	-	1,904.00	-	3,327.00
19	Natural gas	**20.00**	2.63	-	68.02	255.77	2.40	-	4.69	703.64

Based on the numerical results in Table (1), the natural gas consumption for the “reference” drying plant reversible functioning is 5.73 Nm^3/t soybeans and the energy efficiency of the whole plant is 66.3%.

5. Conclusions

The mathematical model presented in this paper captures the basic aspects of soybeans dryers functioning and produces the initial information needed for developing analysis of economical and technical effectiveness of such equipments.

A 100 t/h continuous mixed-flow direct-fired column dryer with forced-air drying and cooling, with four control volumes: (1) the heater, (2) the mixture chamber, (3) the cooling chamber, and (4) the drying “zone”, characteristic for the majority of industrial soybeans dryers in Paraná, Brazil, is considered as “reference” soybeans dryer.

To study grains drying plants with cogeneration it is considered a soybeans dryer physical structure containing a fifth control volume, which is an electrical power generator (e.g., a high-pressure gaseous fuel 330 Capstone Micro Turbine^{TM}).

An eight control volumes configuration is considered for a drying plant with trigeneration: (1) the heater, (2) the mixture chamber, (3) the cooling chamber where the soybeans is cooled to avoid that dry soybeans naturally pick up moisture from the atmosphere during the storage, (4) the drying “zone” where the moisture of grains is effectively removed, (5) an electrical power generator that also produces hot gases for the mixture chamber (e.g., a high-pressure gaseous fuel 330 Capstone Micro Turbine^{TM}), (6) a fuel cell to produce electricity and hot water (e.g., a ONSI Corporation PC25^{TM}C Fuel Cell), (7) an absorption chiller (e.g., a Yazaki Energy Systems, Inc WFC-10 water fired chiller), and (8) a heat exchanger to cool down the atmospheric air that enters the cooling chamber.

Since the energy analysis does not provide a very efficient tool to characterize drying plants with cogeneration and trigeneration, where simultaneously occur generation of electricity, generation of thermal energy for moisture removal, and cold air production, the results provided by the mathematical model presented in this paper are useful for developing exergy analysis of industrial grain dryers functioning.

6. Acknowledgement

The authors gratefully acknowledge the support of FINEP/CTPETRO (Project No. 0660/01).

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