Modeling a Combined Heat and Power Cogeneration System in Vietnam with a Fluidized Bed Combustor Burning Biomass

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ABSTRACT

Agricultural biomass, suitable for the generation of electrical power using a combined heat and power (CHP) plant, is abundantly available in Vietnam. This study used a fluidized bed combustor (FBC) plant with the biomass fuel mixtures hemp residue and rapeseed residue. A theoretical model for the technical parameters of the combustion process and drying system is proposed. The results determine the optimal ratio of each kind of residue to decrease emissions and increase thermal efficiency of the system. The presented model is suitable for experimental investigations, and/or may be applied for the design of a small scale rural power station.

Keywords: Model, combined heat and power-plant, combustion, fluidized bed combustor, drying systems, agricultural residues, biomass

1. INTRODUCTION

With economic development, the energy need for production, particularly in the agricultural industry for processing and storage of agricultural products is increasing rapidly in Vietnam. Traditional energy is mainly thermoelectricity and hydroelectric power (Pham and Thang, 2003). According to the EVN report, up until the end of 1998 the national electrical network supplied only about 93% of households in cities, 72% in villages and 60% of farmer households. Electrical energy used for agricultural production (pumping stations, small home craft, light, and etc.) makes up 13.5-14% (1,870 billion kWh/year) of the total electrical power production (Pham and Thang, 2003 and Nguyen, 2006).

Vietnam has large potential for electricity generation from renewable energy sources such as biomass residues (rice husk, bagasse, coffee husk, cassava, maize, coconut fibre, and straw, wood, etc.) Tung and Steinbrecht et al. (2008) estimated the availability of renewable biomass at approximately 80 million tons/ year (Renewable Energy in Asia: the Vietnam report, 2005; England and Daniel, 1993; Nguyen, 2006; UNDP, 1990). At present, different biomass resources are often used to cook food, raise animals (Tung, Steinbrecht and et al., 2008), make compost, or disposed of in the environment (Pham , 2005 and Nguyen, 2006).

The status of lack of electrical supply will continue in the future (EVN, 2006). Using biomass to produce energy is a promising solution for Vietnam (Tung, Steinbrecht and et al., 2008). Simultaneously electricity generation from biomass can also help solve environmental pollution problems. In the present study, a theoretical CHP-plant model has been developed to calculate the combustion process, steam power station, and drying systems.

2. OUTLINE OF THE SYSTEM MODEL AND TECHNOLOGICAL DIAGRAM

2.1 Representation of the Model

Some modules in this CHP- model are created such as: FBC; steam power process and pneumatic drying cassava starch to export, drying cassava reject to feed cattle (Fig. 1). The diagram of the technological process of the CHP-plant investigated is shown in figure 2.

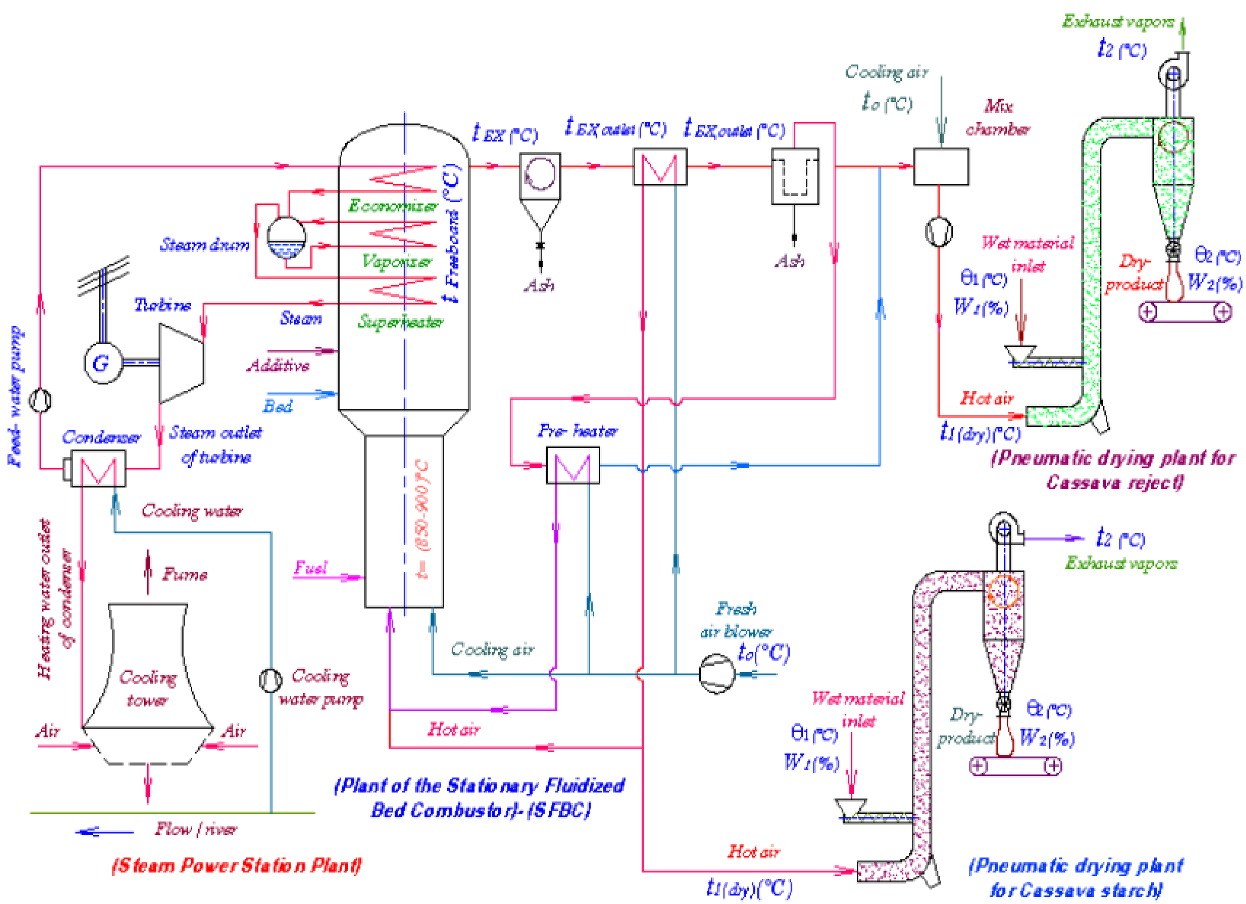

Figure 1. Flow sheet of the combined heat and power plant with FBC with agricultural residues in Vietnam

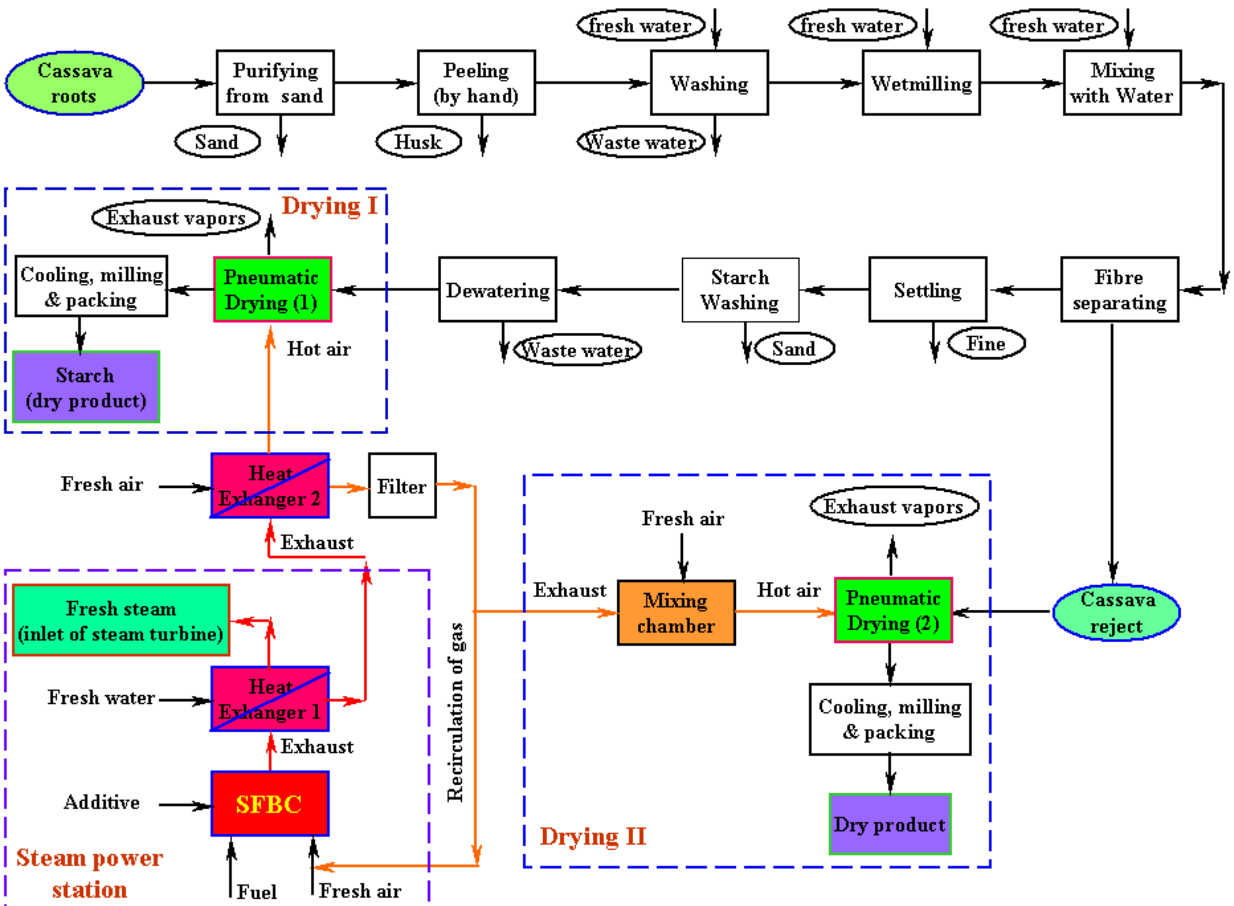

Figure 2. Technological flow sheet of the combination between FBC with steam power station and cassava starch-, cassava reject drying process

2.2 The Target of the Combined Heat and Power Plant

The target of the model is to calculate the burning process of single solid biomasses and the mix of them. In this special case we have investigated hemp residue and rapeseed residue as fuels. On the other hand, the optimal parameters for the burning process of the CHP-plant can be found in this model, for example: combustion air ratio, how to make the best burning effect related to emissions and economics.

Besides, with the help of this model we can find the thermal efficiency, the general efficiency. When mixed fuels are burnt, the necessary optimal rate among the fuels is easily to find.

3. CALCULATION OF HEAT AND POWER COGENERATION SYSTEM

3.1 Calculation of Power Generation System

Representing the process:
The main components of the steam generator are combined with the FBC including: Economiser, super heater, steam turbine combining with the generator, condenser, and feed pump (Fig. 1).

The aim of the steam power process modeling is to find the heat consumption for process steam generation under the given steam parameters (temperature and pressure level) necessary to generate a defined electrical power output with the turbo generation set.
Analysis of the simple ideal steam power process: The simple ideal steam power process (Clausius-Rankine-Cycle) is presented in the diagrams Temperature-Entropy (T, s) and Enthalpy-Entropy (h, s) (Fig. 3).

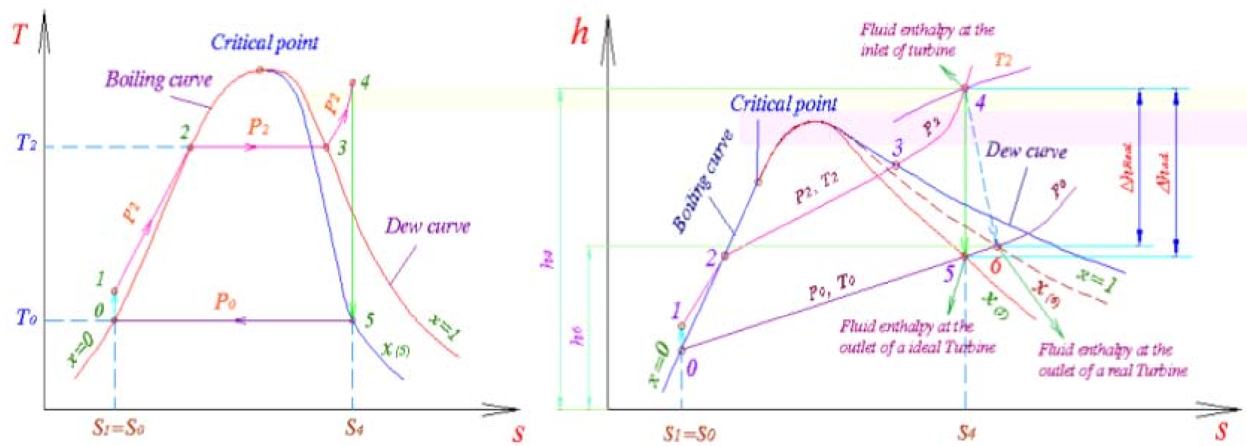

Figure 3. Diagrams (T, s) (left), and (h, s) (right) of Clausius-Rankine-Cycle

- Process 0→1 is isentropic, the pressure at point ''0'' is equal to the pressure at ''5'' ($p_0 = p_5$) (in theory) risen to the operational pressure ($p_S = p_1$),
- Process 1→2 is the isobar heat input, this heat input makes the water warmer. This phase is calculated by the expression (1),

$$Q'_{12} = m'_{FP}.(h'_2 - h_1) = m'_{St}.(1+a).(h'_2 - h_1) \qquad (1)$$

- Process 2→3 is the isobar-isotherm heat input during boiling. This is the steam generator, heat capacity. This phase is calculated by the expression (2),

$$Q'_{23} = m'_{St}.(h''_3 - h'_2) \qquad (2)$$

- Process 3→4 is the super heater, heat input in this phase is calculated by expression (3),

$$Q'_{34} = m'_{St}.(h_4 - h''_3) \qquad (3)$$

Therefore, the necessary heat input of the entire steam generator for electrical generation is calculated by expression (4).

$$Q'_{total,St} = Q'_{12} + Q'_{23} + Q'_{34} \qquad (4)$$

This model can predicted: fuel consumption, steam mass production, electric generation output, and the thermal efficiency of the process. The initial parameters for further calculations are assumed as follows: the temperature of feed water at state ''0'' (Fig. 4), ($t_{Cond.}$ = 35° C is near to the natural water temperature in summer time in Vietnam). Following the technical condition in Vietnam, pressure and superheated steam temperature supply to the steam turbine to generate 2000 kW_{el} are selected at:

Steam parameters p_4 = 26 bar, T_4 = 350° C corresponding to power range 5-50 MW; further the efficiency of the steam turbine η_T = 0.82, mechanical efficiency η_{mech} = 0.99 and efficiency of generator η_G = 0.98 (Schmitz and Schaumann, 2005).

The process is routinely investigated with the help of the EXCEL model supported by visual basic. The last solution of the parameters (the calculation results) of the process is presented in Fig. 4 and Fig. 5, the necessary heat input of the process $Q'_{total,St} \approx 8345$ kJ/s, this parameter is given to calculate the energy balance in the general model later (in chapter 3.4), and the Energy conversion efficiency of the steam power station $\eta_{EC,St} \approx 24.7\%$.

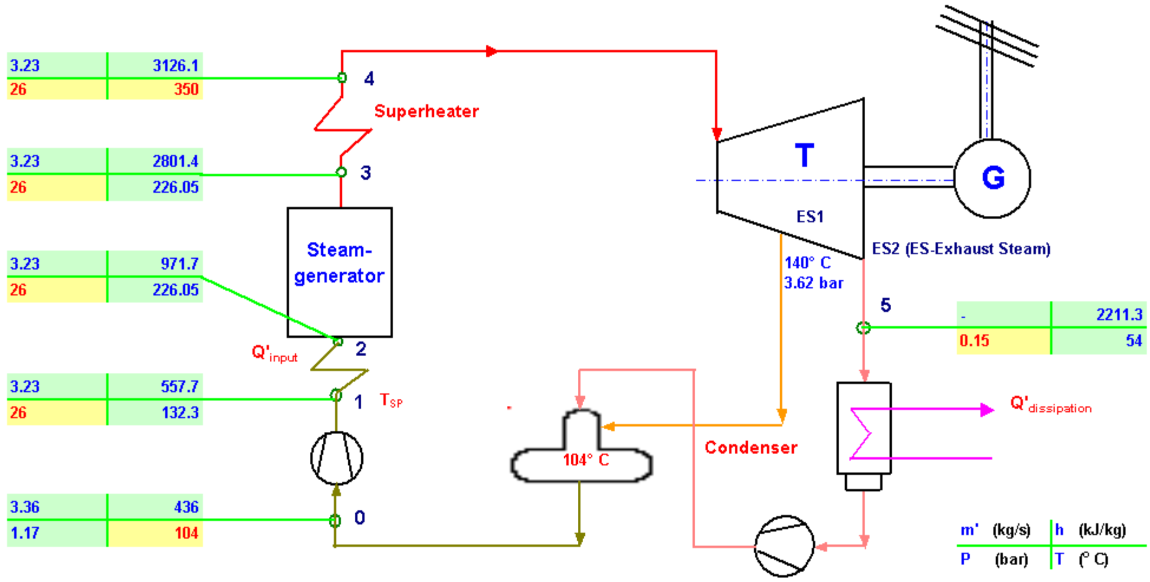

Figure 4. Flow sheet, calculation results and technological parameters of steam cycle

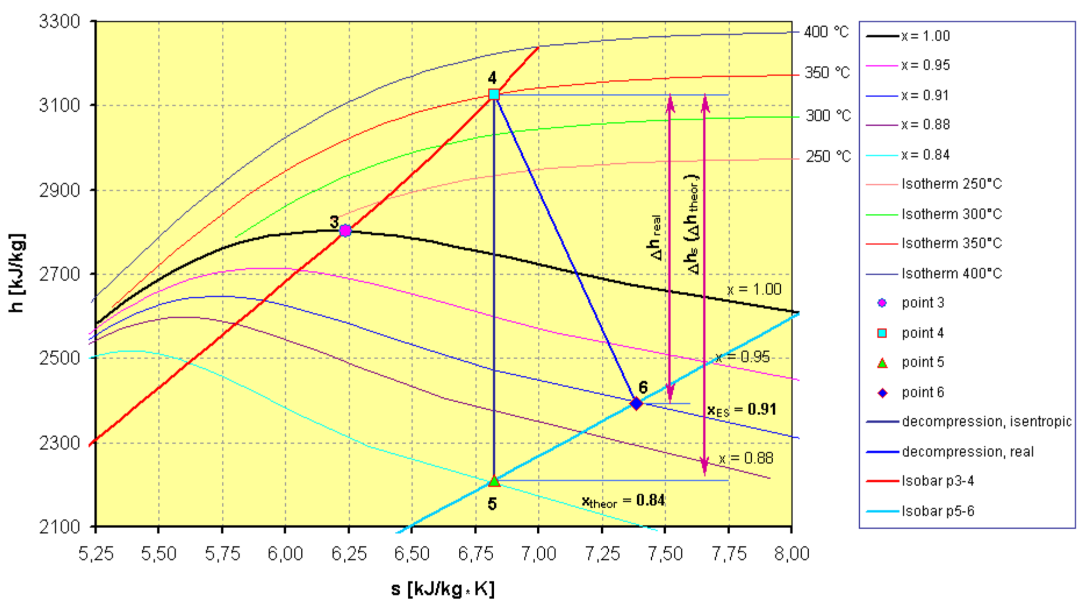

Fig. 5. Calculation results for isentropic and real expansion in the steam turbine presented in h, s-diagram

The flue gas enthalpie after of the last heat exchanger of the steam power process can be used for municipal heating and other technological purposes. Typical example is drying of agricultural products. Here the drying of cassava starch and cassava residues are treated.

3.2 Pneumatic Drying Systems of Cassava Starch, and Cassava Residue

Drying is an energy-intensive process. Well-designed modern drying equipment with high thermal efficiencies using heat energy from biomass combustion are becoming increasingly important. A pneumatic dryer is used in various branches such as: in the chemical, ceramic, and mining industries and especially in food industry for drying grains, tubers and their flours. Pneumatic drying can be classified as a gas-solid transport system which provides a continuous convective heat and mass transfer. For the drying of cassava starch, and cassava residues the transport and heating media is hot air, which is available through indirect heating (Calorifier) and direct heating (by mixing with flue gas in mixing chamber).

The large surface for heat and mass transfer, as well as the high turbulence and relative velocities lead to high drying rates. The size of particulates to be dried is usually in the range of 15-500 μm (Krischer and Kröll, 1959; Van et al., 2006). The special feature of this co-current dryer is the very short contact time (0.5-10 s, Borde and Avi 2006) between the hot air and the particulate materials in the drying chamber. This allows the drying of thermolabile materials. Further the dryer needs only a small installation area and impresses with low capital costs in comparison with other types of dryers.

The simple pneumatic drying system includes six basis components (Fig. 6). The wet particles are fed into the hot air stream. The stream flows up the drying tube with a gas velocity (v_{gas}) that is greater than the free fall velocity (v_{fr}) of the largest particles. Ratios of $v_{gas}/ v_{fr} > 2$ are typical (Krischer and Kröll, 1959).

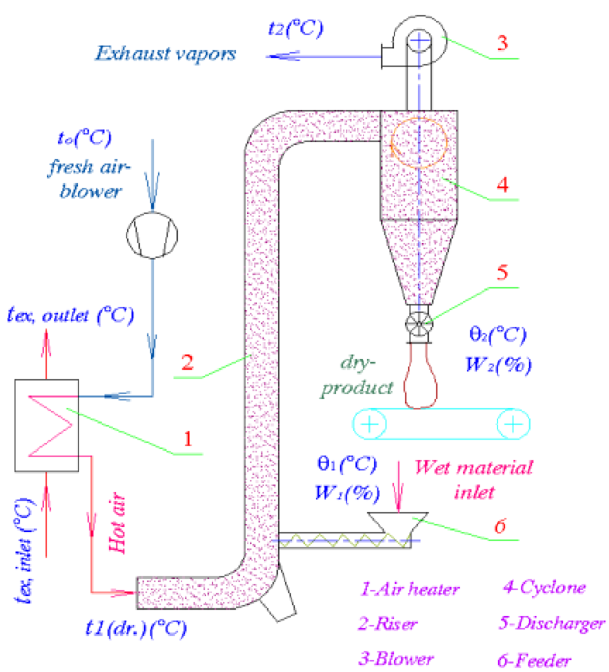

Figure 6. The principle diagram of the pneumatic drying plant

3.2.1 Calculation of pneumatic Drying for Cassava Starch and Cassava Reject

Pneumatic drying is generally described by the equations of convective heat transfer. The total energy input is necessary for: water evaporation, heating up the dry material and heat losses by radiation. The Energetic balance shows appropriate relations between the total provided energy, utilized energy, and heat losses in the drying process.

The simplified drying system modell is composed of four flows i.e. input and output of the drying mediums and the input and output flow of the drying material. The energetic balance system for the two drying section are shown in Figure 7. The main parameters for the calculation are shown in Table 1.

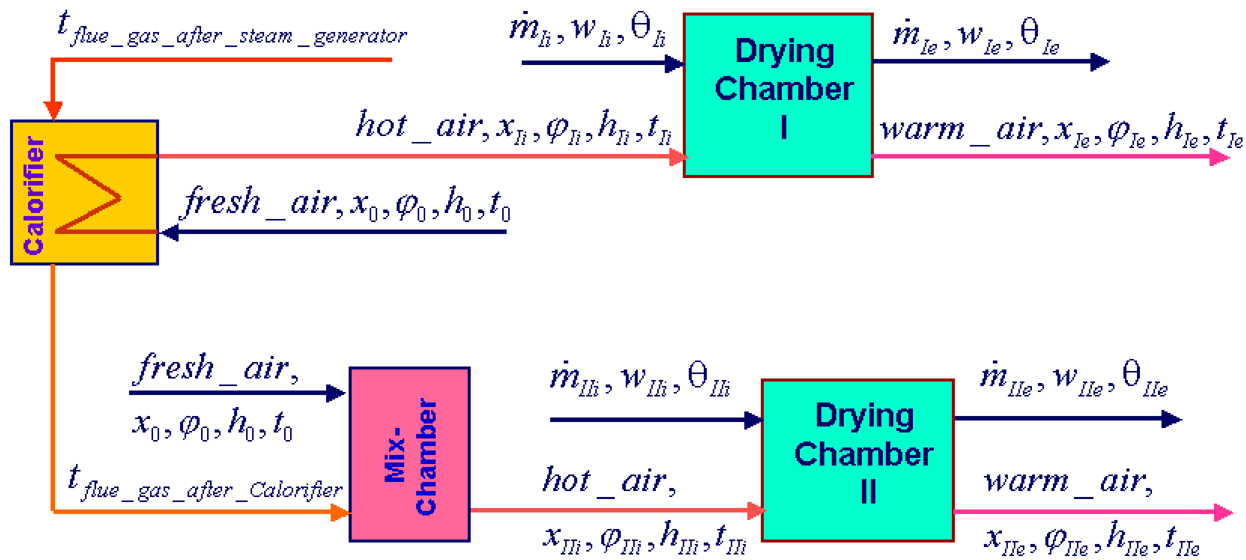

Figure 7. The scheme of energetic balance for the drying systems includes four flows

Table 1. The initial parameters for the calculation of the pneumatic drying of export cassava starch and cassava reject

Parameters	Symbol, Unit	Value (cassava starch drying)	Value (cassava reject drying)
Mass of the cassava- starch, -reject after drying	$m_{2(dr)}$ [kg/s]	0.278	0.278
Temperature of product before drying	θ_1 [° C]	15	20
Temperature of product after drying	θ_2 [° C]	50	60
Content of the wet material at the inlet of dryer *)	w_1 [kg w./kg DS]	0.45	0.65
Content of the wet material at the outlet of dryer *)	w_2 [kg w./kg DS]	0.11	0.13
Air temperature at the inlet of dryer	t_1 [° C]	125	150
Air temperature at the outlet of dryer	t_2 [° C]	50	60
Temperature of pure air before input into heat exchanger (calorifer), and before inside mix chamber	t_0 [° C]	25	25
Humidity of pure air at the inlet of calorifer, and before input into mixing chamber	φ_0 [%]	80	80
Enthalpy of the evaporation water	$h_{v,\,H2O}$ [kJ/kg]	2439	2439
Specific heat capacity of the evaporation water	$c_{p,vapo}$ [kJ kg^{-1} K^{-1}]	1.9	1.9
Specific heat capacity of the water	$c_{p,W}$ [kJ kg^{-1} K^{-1}]	4.187	4.187
Specific heat capacity of the air	$c_{p,air}$ [kJ m^{-3} (N) K^{-1}]	1.3	1.3

*)- Van et al., 2006

The calculation of the drying processes of a given flow rate of drying material leads to the necessary heat consumption. Therefore the calculation equation energetic balance for a drying process is:

$$Q'_{Total(dr)} = Q'_{Evap.} + Q'_{Mater(dr)} + Q'_{Loss(dr)} \quad \text{[kJ/s]} \quad (5)$$

Herewith: $Q'_{Total(dr)}$ - Total heat quantity in [kJ/s],

$Q'_{Evap.}$ - Heat for water evaporation in [kJ/s]

$Q'_{Mater(dr)}$ - Heat for heating of the drying material in [kJ/s],

$Q'_{Loss(dr)}$ - Heat losses in [kJ/s],

1) $$Q'_{Evap.} = W'.(h_{water} + c_{p,m,vapo.}.(\theta_2 - \theta_1)) \quad \text{[kJ/s]} \quad (6)$$

$W' = m'_{1(dr)}.(1-(1-w_1)/(1-w_2))$ - Quantity of evaporated water, [kg/s] (7)

$m'_{1(dr)} = m'_{2(dr)}.(1-w_2)/(1-w_1)$ - Quantity of moist material (before drying), [kg/s] (8)

Where $m'_{1(dr)}$, $m'_{2(dr)}$ are the quantity of material before- and after drying (dry material) (kg/s).

2) $$Q'_{Mater(dr)} = c_{material}.m'_{1(dr)}.(\theta_2 - \theta_1) \quad \text{[kJ/s]} \quad (9)$$

$c_{material} \approx 2.83$ (Krischer and Kröll, 1959) [kJ kg^{-1} K^{-1}] (10)

3) $Q'_{Loss(dr)} / Q'_{Total} = n$ (n = 1.5 - assumption) [%] (11)

Quantity of drying air: $V' = Q'_{Total} / (c_p(t_1 - t_2))$ [m^3/s] (12)

Specific consumption of energy

$$q = Q'_{Total} / W' \quad \text{[kJ/kg]} \quad (13)$$

A schematic h, x- diagram for calculation of the pneumatic drying states is presented in Fig. 8. Method of calculation presented in the following.

The determination of the state points through the process (points 0; 1; 2; 2';3; 4) with the h-x-diagram (MOLLIER) is necessary to derivate the state (esp. gas absolute humidity) of condition after drying and the real specific heat consumption of the dryer.

Point 0 (drying air before heating):
The given parametric pair: (t_0, φ_0), from h, x-diagram results to: h_0, x_0.

Point 1 (heated up air):
The given parametric pair: (t_1, x_0), from h, x-diagram with x = const result to: φ_1, h_1.

Point 2' (theoretical state, adiabatic change of condition):
The given parametric pair: (h_1, t_2), from h, x-diagram with h = constant follows to: $\varphi_{2'}$, $x_{2'}$ or ($x_{2,theor}$, $\varphi_{2,theor}$).
Hence, the specific heat consumption is:

$$q_{theor} = (h_1 - h_0)/(x_{2,theor} - x_0) \quad \text{[kJ/kg]} \quad (14)$$

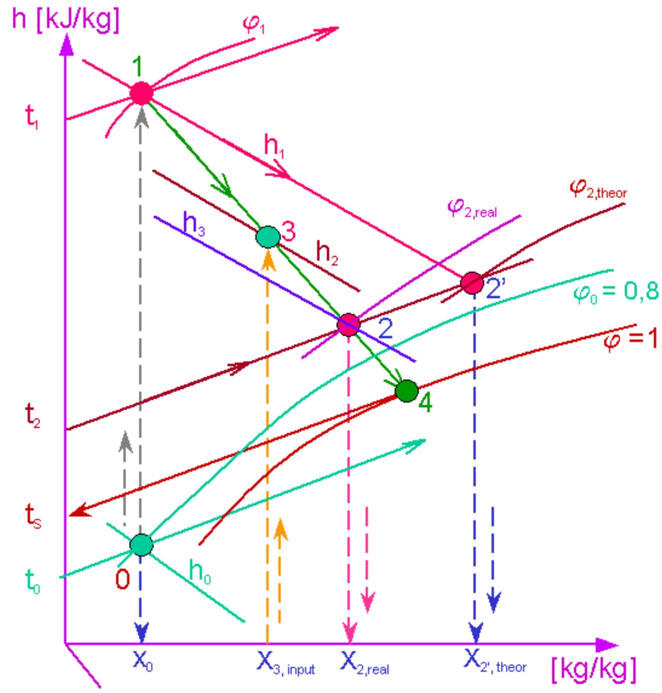

Figure 8. Graphic solution of the drying process in the Mollier-h, x- diagram

Point 3:

The given parametric pair: (h_1, $x_{3,\ input}$), with $x_{3,\ input}$ (free choice in the range of x_0 to $x_{2,theor}$, since the resulting $\Delta q.(x_{3,input} - x_0)$ also fulfils the equation (16 and 17) and leads to enthalpy h_2 according to equation (15) as follows:

$h_2 = h_1 - \Delta q.(x_{3,input} - x_0)$ [kJ/kg] (15)

Δq characterizes the difference between theoretical and real drying heat consumption.

$\Delta q = q_{theor} - q_{real}$ [kJ/kg] (16)

The detailed description of Δq result in the following formulation:

$\Delta q = q_{mater} + q_{Loss} - c_{p,vapo}.\theta_1 = (m^{'}_{1(dr)}.c_{material}(\theta_2 - \theta_1)/W^{'}) + q_{Loss} - c_{p,vapo}.\theta_1$.[kJ/kg] (17)

The loss ratio is: $q_{Loss}/q_{theor} = n$ and will assumed with n = 1.5 %.

Point 2 (real state after drying, non adiabatic change of condition):

The point 1 and point 3 are connected through a line. The line-extension over the intersection with t_2 follows to: φ_2, $x_2 \equiv$ or $x_{2,\ real}$, $\varphi_{2,\ real}$.

Hence, specific consumption of energy and specific enthalpy of the real drying process will be calculation by the following equations:

$q_{real} = q_{theor} - \Delta q$ [kJ/kg] (18)

$h_3 \equiv h_{real} = q_{real}.x_{real}$. [kJ/kg] (19)

Point 4:

The line-extension (point 1, 2, 3) over the intersection with φ = 1 results in t_S (dew point).

3.2.2 Calculation Results

Input parameters: The calculated specific energy consumption is corresponds with the mass of the dry product $m'_{2(dr)} = 0.278$ kg/s (1000 kg/h), the initial parameters can be used for calculation as shown in Table 1. The principle h, x- diagram of the pneumatic drying plant is presented in Fig. 8 and the equations in chapter 3.2.1. The calculation results are presented in Table 2. We have calculated the necessary energy demand to dry $m'_{2(dr)} = 0.278$ kg/s (dry weight) of the product as follows:

- Cassava starch drying: with the initial humidity $w_1 = 0.45$ kg w/kg DS to the maintaining humidity $w_2 = 0.11$ kg w/kg DS. The is $Q'_{dr1} \approx 481.9$ kJ/s.
- Cassava rejects drying: from the initial humidity $w_1 = 0.65$ kg w/kg DS to the maintaining humidity $w_2 = 0.13$ kg w/kg DS. The energy demand is $Q'_{dr2} \approx 1154.5$ kJ/s.

The value Q'_{dr1} and Q'_{dr2} will be the parameter to calculate the energy balance in the general model (CHP-model) later (in chapter 3.4).

Table 2. The main calculation results for drying cassava starch and cassava reject

Parameters	Symbol	Unit	Value (dr. 1)	Value (dr. 2)
Quantity of moist material (before drying) (equ. 8)	$m'_{1(dr)}$	[kg/s]	0.45	0.69
Quantity of evaporated water (equ. 7)	W'	[kg w. vapour /s]	0.17	0.41
Specific heat capacity of the material (equ. 10)	c_{mater}	[kJ kg^{-1}K^{-1}]	2,83	2,83
Heat for water evaporation (equ. 6)	$Q'_{Evap.}$	[kJ/s]	430.24	1037.94
Heat for heating of the drying material (equ. 9)	$Q'_{Mater\ (dr)}$	[kJ/s]	44.44	78.16
Heat losses (equ. 11)	$Q'_{Loss(dr)}$	[kJ/s]	7.23	17.00
Total heat quantity (equ. 5)	$Q'_{Total\ /(dr)}$	[kJ/s]	**481.9**	**1133.1**
Quantity of drying air (equ. 12)	V'	[m^3 dr. Air /s]	4.9	9.7
Specific consumption of energy (equ. 13)	q	[kJ/kg vapour]	**2806.4**	**2745.6**
Gas absolute humidity (in point 0) (h, x-diagram)	x_0	[kg w. V./kg dr. Air]	0.015	0.015
Gas absolute humidity (in point 2') (h, x-diagram)	$x_{2,\ theor}$	[kg w. V./kg dr. Air]	0.050	0.058
Gas absolute humidity (in point 2) (h, x-diagram)	$x_{2,\ real}$	[kg w. V./kg dr. Air]	0,043	0.045
Specific enthalpy (in point 0) (h, x-diagram)	h_0	[kJ/kg dr. Air]	65	65
Specific enthalpy (in point 1, and 2') (h, x-diagram)	h_1	[kJ/kg dr. Air]	173,3	196
Specific enthalpy (in point 3) (equ. 15)	h_2	[kJ/kg dr. Air]	166.6	189.8
Specific enthalpy (in point 2) (equ. 19)	h_3	[kJ/kg dr. Air]	121.2	125.9
Specific consumption of energy of theory drying process (equ. 14)	$q_{theor.}$	[kJ/kg vapour]	3094.3	3046.5
Specific consumption of energy of real drying process (equ. 18)	q_{real}	[kJ/kg vapour]	2817.6	2798.4
Different in specific consumption of energy between theory- and real- drying process (equ. 17)	Δq	[kJ/kg vapour]	276.7	248.1

Dr. 1 is cassava starch drying, dr. 2 is cassava reject drying

3.3 Calculation of Combustion System for agricultural Residues in FBC

Properties of fuels: The fuels used for calculations are rapeseed residue and hemp residues and the mix of them. Both of these fuels have similar properties to other agricultural plants. These materials can be used to process fibers, paper (hemp residues), animal food or compost (rape seed residues). They can also be used as FBC feedstock to generate heat, electrical energy or combined heat and power cogeneration. The chemical and physical properties i.e. carbon (C), oxygen (O), hydrogen (H), nitrogen (N), sulphur (S), ash (a), and water (w) contents and the ISO: net calorific value (NCV) of these fuels are analyzed and compared with the main biomasses of Vietnam i.e. rice husk, bagasse, coconut shells, and cassava residues (Tung, Steinbrecht and et al., 2008) as shown in table 3. The comparison shows that the properties of biomasses are very similar. Nevertheless the ash content can be different. All values are produced in own analyses.

Table 3: Comparing the chemical compositions of biomasses (w, fuel-moisture; a, fuel-ash)

Component Fuels	(C) (kg/kg)	(H) (kg/kg)	(O) (kg/kg)	(N) (kg/kg)	(S) (kg/kg)	(a) (kg/kg)	(w) (kg/kg)	(NCV) (kJ/kg)
Hemp residue [1), a)]	0.4429	0.0613	0.3488	0.0036	0.0009	0.0187	0.1238	16,236
Rapeseed residue [2), a)]	0.4670	0.0633	0.2177	0.0575	0.0001	0.0693	0.1251	18,086
Mix (1&2), ratio [0.57: 0.43]	0.4566	0.0624	0.2741	0.0343	0.0004	0.0475	0.1245	17,291
Rice husks [b)]	0.3979	0.0523	0.3863	0.0013	-	0.1392	0.0230	15,196
Coconut shells [b)]	0.4622	0.0520	0.4163	0.0026	-	0.0300	0.0369	17,408
Cassava residues [b)]	0.4434	0.0576	0.4237	0.0065	-	0.0450	0.0238	15,942
Bagasse [b)]	0.4638	0.0576	0.4519	-	-	0.0074	0.0193	16,686

[1)]- Fuel 1; [2)]- Fuel 2; [a)]- Fuels grown in Germany; [b)]- Fuels of Vietnam

Model investigations of the firing process: The used general heat capacity and the chemical, physical, NCV of fuels are the input parameters to calculate the energy balance of the entire system.

The “normal” SFBC combustion temperature is 850° C. Depending on ash properties (e.g. its ash melting point) we have to realize lower combustion temperatures e.g. between 780 … 850° C. The combustion quality needs to be supervised and, if necessary, be influenced by SFBC operational measures.

With the assumed initial condition temperature in FBC T_{FB}= 835° C (with biomass), the result show that a fuel mass flow of approximately 0.58 kg/s (2088 kg/h) is necessary, this corresponds to a primary fuel energy of 9708 kW. The oxygen concentration in exhaust has been varied from 3-11 Vol. %. The temperature of recirculation exhaust was kept at T_{RC} = 170° C = const. and the mass flow of the recirculation gas was varied (T_{RC} is the temperature of flue gas at the exit of calorifier before entering the mixing chamber, see No. 4 in Fig. 9). In the mixing chamber pure cold air is mixed with warm air-exhaust to supply the drying step for cassava reject.

Under these conditions the model presented above finds the solution for the necessary flow rate of exhaust recirculation gas (RC) ≈ 1.4-0.4 m^3 (N)/m^3 (N), and flow ($V'_{EX,\,RC}$) ≈ 5.2-2.7 m^3 (N) EX/s , respectively (Table 4). The efficiency, electrical efficiency of entire system and CO_2 & SO_2 emission components from combustor will be presented later, in chapter 3.4.

Table 4. Calculated model results for the variation of $O_{2,EX,dr}$ from 3.0 to 11.0 Vol. %

Parameter Input	$Q'_{Use} = P_{el.} + Q'_{dry1} + Q'_{dry2}$ [kW]				3636		
	m'_{Fuel}	[kg/s]			0.58		
	Q'_{Fuel}	[kW]			9708		
	T_{RC}	[° C]			170		
	$O_{2,EX,dr}$	[Vol. %]	3.0	5.0	**7.0**	9.0	11.0
Parameter Finding	RC	[m^3 (N)/m^3 (N)]	1.4498	1.2170	**0.9718**	0.7138	0.4417
	$V'_{EX,RC}$	[m^3 (N) EX/s]	5.1792	4.8146	**4.3241**	3.6457	2.6627
	T_{FB}	[° C]			**835**		

$T_{After\ Steam\text{-}Power}$	[° C]	224	219	**213**	205	193
Q'_{Input}	[kW] (equ. 33)	11116	11046	**10953**	10827	10648
η_{Use}	[%], (equ. 35)	32.7	32.9	**33.2**	33.6	34.2
$\eta_{el.}$	[%], (equ. 36)	18.0	18.1	**18.3**	18.5	18.8

3.4 Investigation and Optimization of Heat and Power Cogeneration Process

Figure 9 shows results of the combined heat and power plant with flue gas recirculation. That includes: 1- combustion chamber; 2-steam generator; 3- heat exchanger that makes pure warm air for the cassava starch drying plant; 4-mixing chamber that makes the mix of warm air-exhaust to dry cassava reject to make cattle food.

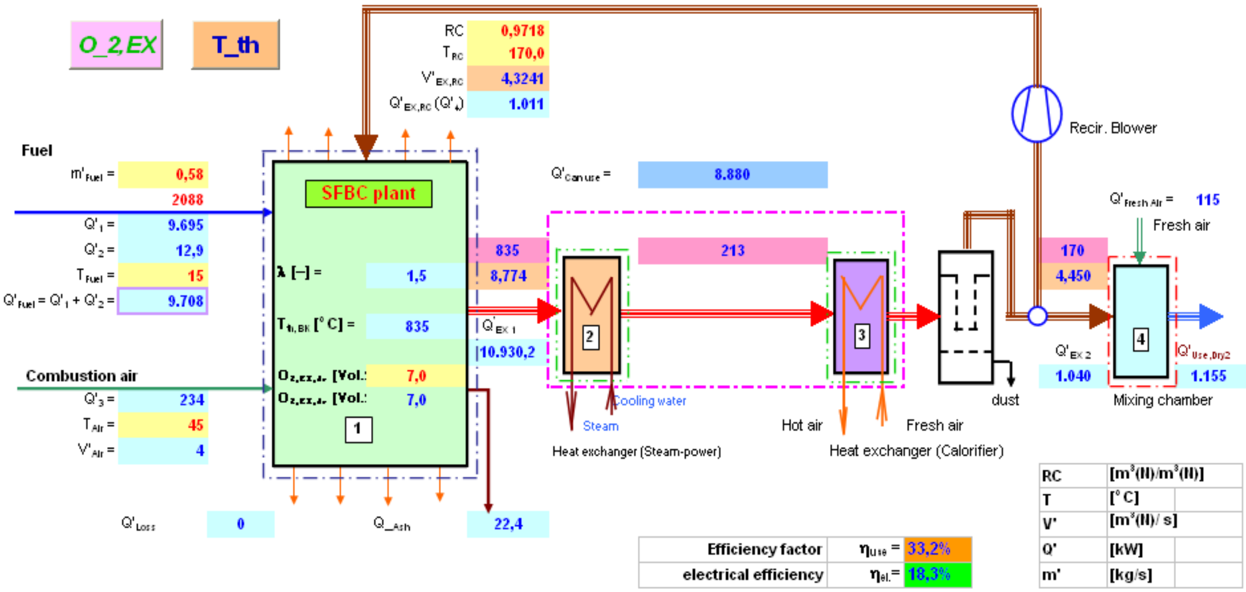

Figure 9. Diagram, interface indicates the results of the CHP-plant model. From the left (figure above): this model includes modules: 1- combustion chamber; 2- steam generator; 3- heat exchanger that makes pure warm air for the cassava starch drying plant; 4-mixing chamber to make the mix of warm air-exhaust to dry cassava reject

The energy balance of the CHP-System is shown in Figure 10, there are energy balances in the combustion chambers (a), heat exchanger (b) and mixing-chamber (c).

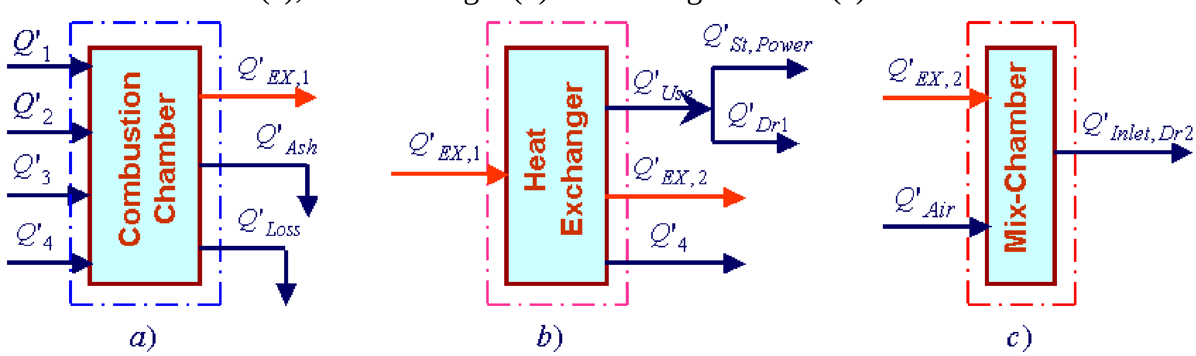

Figure 10. The scheme of energetic balance for the modules of the CHP-System

The equations (related to 0° C) used to calculate energy balance for the CHP-model in Fig. 9 & 10 are described (Steinbrecht, 2008[a], and 2008[b]) as follows. The calculation results are shown e.g. in Fig.9, and Table 4 to 6.

- Chemical energy of fuel:

$$Q'_1 = m'_{Fuel}.Hu \quad \text{(kW)} \quad (20)$$

- with heat content/thermal capacity the supply energy of fuel:

$$Q'_2 = m'_{Fuel}.c_{Fuel}.T_{Fuel} \quad \text{(kW)} \quad (21)$$

- heat capacity of air:

$$Q'_3 = m'_{Fuel}.\lambda.L_{\min}.c_{pm,Air}.T_{Air} \quad \text{(kW)} \quad (22)$$

- recirculation of heat capacity of exhaust:

$$Q'_4 = Q'_{EX,RC} = RC.m'_{Fuel}.V_{m(\lambda)}.h_{EX,RC} \quad \text{(kW)} \quad (23)$$

- energy in the exhaust 1:

$$Q'_{EX,1} = (1+RC).m'_{Fuel}.V_{m(\lambda)}.c_{pm,EX}.T_{th,BK} \quad \text{(kW)} \quad (24)$$

- energy in the ashes :

$$Q'_{Ash} = m'_{Fuel}.a_{Fuel}.c_{Ash}.T_{th,BK} \quad \text{(kW)} \quad (25)$$

- heat losses:

$$Q'_{Loss} = n.Q'_{Access}, \quad \text{(n- coefficient acceptance)} \quad \text{(kW)} \quad (26)$$

- useful heat output 1:

$$Q'_{Use} = Q'_{Steam\_Power} + Q'_{dry1} \quad \text{(kW)} \quad (27)$$

- energy in the exhaust 2:

$$Q'_{EX,2} = m'_{Fuel}.V_{m(\lambda)}.c_{pm,RC}.T_{RC} \quad \text{(kW)} \quad (28)$$

Equation of energy balance for CHP-System is (13) or (16):

$$Q'_{Balance} = Q'_{Debit\_value} - Q'_{Actual\_value} = 0 \quad \text{(kW)} \quad (29)$$

with : $Q'_{Debit\_value} = Q'_1 + Q'_2 + Q'_3 + Q'_4$ (kW)- Input energy, and (30)

$Q'_{Actual\_value} = Q'_{EX,1} + Q'_{Loss} + Q'_{Ash}$ (kW) Output energy (31)

or: $Q'_{Balance} = Q'_{Access} - Q'_{Egression} = 0$ (kW) (32)

with: $Q'_{Access} = Q'_1 + Q'_2 + Q'_3 + Q'_4$ (kW) Input energy, and (33)

$Q'_{Egression} = Q'_{Loss} + Q'_{Ash} + Q'_{Use} + Q'_{EX,2}$ (kW) Output energy (34)

Efficiency factor: $$\eta_{Use} = \frac{(P_{el.} + Q'_{dry1} + Q'_{dry2})}{Q'_{Access}} \quad (\%) \quad (35)$$

Electrical efficiency: $$\eta_{el.} = \frac{P_{el.}}{Q'_{Access}} \quad (\%) \quad (36)$$

The total useful heat calculated from The Power Generation System (chapter 3.1) and the Drying Systems (chapters 3.2.1 and 3.2.2) is the input parameter for the model calculated in equations (20) to (36).

The results were achieved with the model presented above by varying the input parameters. The results can be described as follows.

Table 5 presents the solution for RC, $V'_{EX,RC}$ and η at constant oxygen concentration in exhaust ($O_{2,EX,dr}$) = 6 Vol. % for varying recirculation temperature T_{RC} in the interval of 150, 160… 200° C. For this investigation the combustion temperature T_{FB} is always 835° C = const. In principle, the lower limit of T_{RC} must be smallest at 150° C, which is equal to the necessary temperature to supply for the cassava reject drying plant. The upper limit should not be greater than 200° C, because of the negative economic effect resulting in the increasing demand for pure air addition to supply input temperatures at 150° C for the drying chamber.

Table 5. Model results of the firing process with varied T_{RC}

Parameter Input	$Q'_{Use} = P_{el.} + Q'_{dry1} + Q'_{dry2}$	[kW]	3636					
	m'_{Fuel}	[kg/s]	0.58					
	Q'_{Fuel}	[kW]	9708					
	$O_{2,EX,dr}$	[Vol. %]	6.0					
	T_{RC}	[° C]	150	160	**170**	180	190	200
Parameter Finding	RC	[m^3 (N)/m^3 (N)]	1.0650	1.0827	**1.0960**	1.1115	1.1270	1.1437
	$V'_{EX,RC}$	[m^3 (N) EX/s]	4.4585	4.5326	**4.5883**	4.6532	4.7181	4.7880
	T_{FB}	[° C]	**835**					
	$T_{After\ Steam\text{-}Power}$	[° C]	207	212	**217**	221	226	231
	Q'_{Input}	[kW] (equ. 34)	10847	10926	**11002**	11083	11166	11252
	η_{Use}	[%], (equ. 35)	33.5	33.3	**33.1**	32.8	32.6	32.3
	$\eta_{el.}$	[%], (equ. 36)	18.4	18.3	**18.2**	18.0	17.9	17.8

Table 6 shows the influence of RC (at constant temperature T_{RC}) on $O_{2,EX,dr}$. Further, this table presents the changes of $V'_{EX,RC}$ and η connected with the changes of RC.

Table 6. Results for the variation of RC

Parameter Input	$Q'_{Use} = P_{el.} + Q'_{dry1} + Q'_{dry2}$	[kW]	3636					
	m'_{Fuel}	[kg/s]	0.58					
	Q'_{Fuel}	[kW]	9708					
	T_{RC}	[° C]	170					
	RC	[m^3 (N)/m^3 (N)]	0.00	0.25	0.50	0.75	**1.00**	1.25
Parameter Finding	$O_{2,EX,dr}$	[Vol. %]	14.032	12.347	10.582	8.722	**6.775**	4.722
	$V'_{EX,RC}$	[m^3 (N) EX/s]	0.0	1.7223	2.9034	3.7524	**4.3871**	4.8716
	T_{FB}	[° C]	**835**					
	$T_{After\ Steam\text{-}Power}$	[° C]	160	181	196	206	**214**	220
	Q'_{Input}	[kW] (equ. 33)	10174	10480	10692	10846	**10964**	11057
	η_{Use}	[%], (equ. 35)	35.7	34.7	34.0	33.5	**33.2**	32.9
	$\eta_{el.}$	[%], (equ. 36)	19.7	19.1	18.7	18.4	**18.2**	18.1

After calculating the energy balance of the entire CHP-plant, the process is investigated when we change T_{RC} from 150° C to 200° C, or $O_{2,EX,dr}$ from 3.0 to 11.0 Vol.%, or RC from 0.0 to 1.25

m^3 (N)/m^3 (N). The results are shown in table 4 to table 6. Subsequently the solution for $O_{2,EX,dr}$ in exhaust of the burning process is approximately 6.0-7.0 Vol.%, T_{RC} = 170° C, RC ≈ 0.97-1.1 m^3 (N)/m^3 (N), $V'_{EX,RC}$ ≈ 4.6-4.3 m^3 (N) EX/s, and $T_{After,St-P}$ ≈ 217-213° C. The over-all efficiency of the process is $\eta_{total} \equiv \eta_{use}$ of approximately 33.1-33.2% (the Energy conversion efficiency of the steam cycle alone ($\eta_{EC,St}$) is approx. **24.7%** (in chapter 3.1)), and electrical efficiency $\eta_{el.}$ ≈ **18.2-18.3%.**

Figure 11 indicates the relationship between temperature and thermal power. The steam is generated with a generator thermal efficiency of $\eta_{St,G}$ = 76.2%. The efficiency used for the cassava starch drying plant is η_{dr1} = 4.4%, and for the cassava reject drying plant η_{dr2} = 10.5%. The general efficiency is used for the entire plant $\eta_{total} = (\eta_{St,G} + \eta_{dr1} + \eta_{dr2})$ = 91.1%. The heat losses then make up only 8.9%.

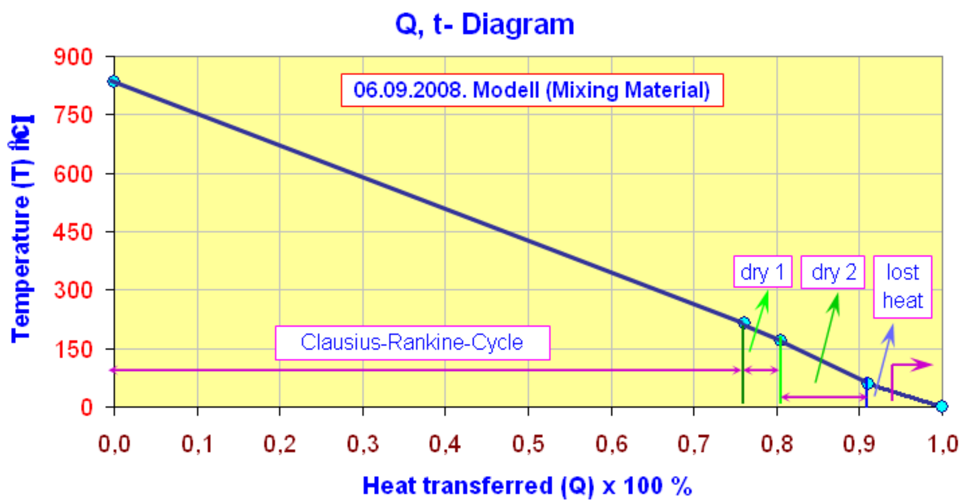

Fig. 11. Relation between the temperature of plant and the used heat Q = f(T) when T_{FB} = 835° C

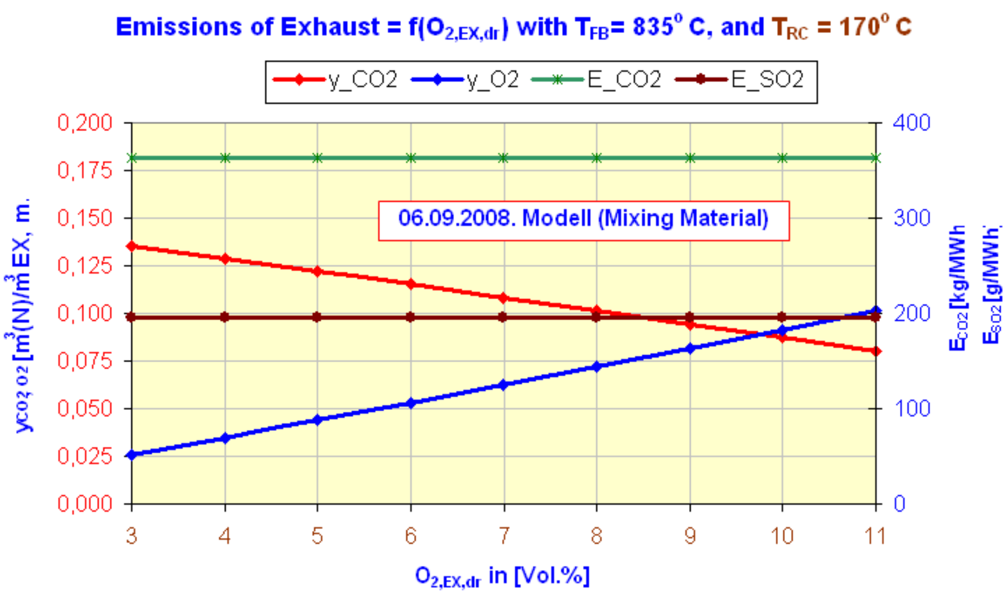

Fig. 12. Exhaust emissions depending on $O_{2,EX,dr}$ when T_{FB} = 835° C, T_{RC} = 170° C

Last is the figure indicating the relation of exhaust emission components and concentration in the exhaust (such CO_2, O_2, E_CO_2, and E_SO_2). Following the calculation of this model, example with T_{RC} = 170° C (Fig. 12). This figure shows that the rate of CO_2 will decrease from 0.14 [m^3 (N)/m^3 (N) EX, humid] (with $O_{2,EX,dr}$ = 3 Vol. %) to 0.08 [m^3 (N)/m^3 (N) EX, humid] (with $O_{2,EX,dr}$ = 11 Vol. %), and E_CO_2 ≈ 363 kg/MWh, E_SO_2 ≈ 196.2 g/MWh (92.7 mg/m^3(N) EX) < 350 mg/m^3(N)EX (TA Luft, 2002).

From the calculation results:

- Power Generation Ratio is (Karl, 2004):

$$X_{Po} = \frac{Q'_{Steam}}{Q'_{Steam} + Q'_{Use,heat}} = \frac{Q'_{Steam}}{Q'_{Steam} + Q'_{dry1} + Q'_{dry2}} = \frac{8345kW}{(8345kW + 481.9kW + 1154.5kW)} = 0.84 \quad (37)$$

Where: Q'_{Steam} - Thermal power of the steam-power station in (kW),

$Q'_{Use,heat}$ - Thermal power of useful heat output in (kW),

Q'_{dry1} - Thermal power to cassava starch drying system in (kW),

Q'_{dry2} - Thermal power to cassava rejects drying system in (kW).

The heat generation ratio is then:

$$X_H = 1 - X_P = 1 - 0.84 = 0.16 \quad (38)$$

- According (Karl, 2004), the definitional ratio of electricity is: the ratio of electric power $P_{el.}$ divided by the sum of total of electric power and useful heat output $Q'_{Use,heat}$ generated

$$e = \frac{P_{el.}}{P_{el.} + Q'_{Use,heat}} = \frac{P_{el.}}{P_{el.} + Q'_{dry1} + Q'_{dry2}} = \frac{2000kW}{(2000kW + 481.9kW + 1154{,}5kW)} = 0.55 \quad (39)$$

with: $P_{el.}$ - Net electric power in ($kW_{el.}$),

- CHP coefficient is that the ratio of electric power $P_{el.}$ is divided for useful heat output $Q'_{Use,heat}$ generated (Karl, 2004):

$$\sigma = \frac{P_{el.}}{Q'_{Use,heat}} = \frac{P_{el.}}{(Q'_{dry1} + Q'_{dry2})} = \frac{2000kW}{(481.9kW + 1154.5kW)} = 1.22 \quad (40)$$

The above results show that in the CHP-model the thermal power was used for generating electric power, which is the main target. The secondary target is to utilize the rest thermal power for drying purposes.

4. CONCLUSIONS

The necessary main technical parameters of the CHP-plant can be determined from the theoretical model calculations.

The flue gas heat energy after the SFBC reactor can be used for heating and other technological purposes. A typical example is drying of agricultural products.

To generate 2000 kW_{el} output power requires approximately 8345 kJ/s of heat input. Drying 1000 kg/h cassava starch product consumes a heat input of about 481.9 kJ/s. Drying 1000 kg/h cassava reject products consumes a heat input of about 1154.5 kJ/s. The fuel mass flow required for the combustor is about 0.58 kg/s (2088 kg/h), which corresponds to a necessary fuel energy of about 9708 kW (with T_{RC}= 170° C, and RC = 0.97 to 1.1). The total thermal efficiency of the plant is about 91.1% and the heat loss is approximately 8.9%. From model process investigations the optimal solution of parameters such as: $O_{2,EX,dr}$ in exhaust ≈ 7 Vol. % (correlative with air/fuel ratio $\lambda \approx 1.5$), RC ≈ 1.0 m^3 (N)/m^3 (N), and the general efficiency of entire plant is about 33.2%. The electrical efficiency of plant is about 18.3%, $T_{After,St\text{-}P} \approx 213°$ C, and the optimal mix between fuel 1/fuel 2 is 0.57/0.43 with emissions E_CO_2 of about 363 kg/MWh and stoichiometric E_SO_2 of about 196.2 g/MWh (92.7 mg/m^3 (N) Ex).

Theoretical results have shown that the SO_2- emission in the flue gas is lower than the legal limit of the German emission limit (TA- Luft, 2002, "Technische Anleitung zur Reinhaltung der Luft" the limit is 350 mg/m^3 (N) Ex). The model calculations are based on the heat inputs of the modules. The energy balance of the plant can be automatically calculated with the integrated macro visual basic-excel when parameters such as heat requirement by the CHP-plant are changed, or for different fuels. The model calculations can be applied to increase the plant efficiency, thus reducing costs and increasing economic performance during experimental and operational practice.

The SFBC process is very well suited for the application of agricultural residues as a fuel, and can be used in Vietnam and other developing countries. Especially future attention should be focused on combined production of thermal and electric energy-CHP.

The model calculations showed how the combustion process affects parameters such as burning "Temperature", temperature of recirculation exhaust, ratio of recirculation exhaust, and available "Oxygen" concentration with respect to the characteristic of material. These parameters have a strong effect on flue gas emissions. The parameters of results calculated from theoretical model can be compared to experimental: O_2- concentration in flue gas, thermal process efficiency (η_{th}) and thermal using efficiency (η_{Use}).

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Nomenclature

φ: [%], relative humidity of the process air
θ_1: [°C], temperature of product before drying
θ_2: [°C], temperature of product after drying

a: [-], coefficient acceptance
a_{Fuel}: [kg/kg], ratio mass of ash in fuel
c_{Ash}: [kJ kg^{-1} K^{-1}], specific heat capacity of ash
c_{Fuel}: [kJ kg^{-1} K^{-1}], specific heat capacity of fuel
CHP: Combined Heat and Power
$c_{material}$: [kJ kg^{-1} K^{-1}], specific heat capacity of the material (product after drying)
CO_2: Carbon dioxide
$c_{p,vapo}$: [kJ kg^{-1} K^{-1}], specific heat capacity of the evaporation water
$c_{p,W}$: [kJ kg^{-1} K^{-1}], specific heat capacity of the water
$c_{pm,Air}$: [kJ m^{-3} (N) K^{-1}], specific heat capacity of air
$c_{pm,EX}$: [kJ m^{-3} (N) K^{-1}], specific heat capacity of exhaust
$c_{pm,RC}$: [kJ m^{-3} (N) K^{-1}], specific heat capacity of recirculation exhaust
dr_1: Drying for cassava starch
dr_2: Drying for cassava reject
e: [-], definitional ratio of electricity
E: Emission
E_CO_2: Emission of carbon dioxide
E_SO_2: Emission of sulfur dioxide
EVN: The General Electric Company of Vietnam
h: [kJ/kg], enthalpy, general
h''_3: [kJ/kg], enthalpy at point (3)
h'_2: [kJ/kg], enthalpy at point (2)
h_0: [kJ/kg dr. Air], enthalpy at point (0)
h_1: [kJ/kg], [kJ/kg dr. Air], enthalpy at point (1)
h_4: [kJ/kg], enthalpy at point (4)
$h_{EX,RC}$: [kJ/kg], enthalpy of recirculation exhaust
Hu: [kJ/kg], net calorific value of fuel
h_{water}: [kJ/kg], enthalpy of the evaporation water
kg/h: Kilogram per hour (s)
kW: Kilowatt (s)
kWh: Kilowatt-hour (s)
L_{min}: [m^3(N)/kg fuel], minimal air consumption
m’: [kg/s], mass flow rate
$m'_{1(dr)}$: [kg/h], mass of the cassava starch/cassava reject before drying
$m'_{2(dr)}$: [kg/h], mass of the cassava starch/cassava reject after drying
m'_{FP}: [kg/s], mass flow of feed-water pump
m'_{fuel}: [kg/h], mass fuel flow need to be supplied
m'_{St}: [kg/s], mass flow of Steam
m^3 (N): Normal cubic meter
m^3 (N)EX/s: Normal cubic meter of exhaust per second
mg/m^3: Milligram per cubic meter
MW: Megawatt (s)
MWh: Megawatt-hour (s)
n: [-], coefficient acceptance
NCV: Net Calorific Value

$O_{2,EX,dr}$: [Vol. %], oxygen of exhaust- dry
O_2: Oxygen
p: [bar], pressure
$P_{el.}$: [KW_{el}], net electric power
q: [kJ/kg V], specific heat requirement/ (specific consumption of energy)
Q': [kW], heat capacity
Q'_1: [kW], chemical energy of fuel
Q'_2: [kW], heat content/thermal capacity the supply energy of fuel
Q'_3: [kW], heat capacity of air
Q'_4: [kW], heat capacity of recirculation exhaust
Q'_{Access}: [kW], total heat capacity input
$Q'_{Actual\ value}$: [kW], total output energy
Q'_{Ash}: [kW], energy in the ashes
$Q'_{Balance}$: [kW], heat capacity of energy balance for CHP-System
$Q'_{Debit\ value}$: [kW], total input energy
Q'_{dry1}: [kW], heat transfer rate to cassava starch drying system
Q'_{dry2}: [kW], heat transfer rate to cassava reject drying system
$Q'_{Egression}$: [kW], total heat capacity output
$Q'_{EX,1}$: [kW], heat capacity of exhaust after combustion chamber
$Q'_{EX,2}$: [kW], heat capacity of exhaust after calorifier (heat exchanger)
Q'_{fuel}: [kW], heat energy of fuel
Q'_{Loss}: [kW], heat capacity loss
$Q'_{Steam\ Power}$: [kW], heat quantity of the steam-power station
$Q'_{total,St}$: [kW], total of heat quantity for steam-power station
$Q'_{Use,heat}$: [kW], heat quantity of useful heat output
RC: [m^3 (N)/m^3 (N)], the rate of necessary recirculation exhaust
s: [kJ kg^{-1} K^{-1}], entropy, general
SFBC: Stationary Fluidized Bed Combustor/Combustion
SO_2: Sulfur dioxide
T: [^oC], temperature, general
t_0: [$^\circ$C], temperature of fresh air/ (pure air)
t_1: [$^\circ$C], air temperature at the inlet of dryer
t_2: [$^\circ$C], air temperature at the outlet of dryer
$T_{After\ steam}$: [$^\circ$C], temperature flue gas after steam generator (before input into calorifier)
T_{Air}: [$^\circ$C], temperature of air
TA-Luft: (de. Technische Anleitung zur Reinhaltung der Luft), (engl. Technical Instructions on Air Quality/German Emission Limit)
t_{EX}: [$^\circ$C], temperature of exhaust
T_{FB}: [$^\circ$C], temperature of fluidized-bed-combustion
T_{Fuel}: [$^\circ$C], temperature of fuel
T_{RC}: [$^\circ$C], temperature of recirculation exhaust
$T_{th,BK}$: [$^\circ$C], theoretical temperature in combustion chamber
$V'_{EX,RC}$: [m^3(N)EX/s], recirculation exhaust flow
$V_{m(\lambda)}\equiv V_{EX,h}$: [$m^3(N)EX_h$/kg fuel], volume of per kg fuel emerging of humid exhaust gases
W': [kg/s], Quantity of evaporated water

w_1:	[kg **w**ater / kg **d**ry **s**olids] ≡ [kgW/kg DS], humidity of product before drying
w_2:	[kgW/kg DS], humidity of product after drying
x:	[g/kg], [kg w.V/kg dr.Air], water vapor content in g/(kg) per kg dry air of the process air/(gas absolute humidity)
X_H:	[-], **H**eat generation ratio
X_{Po}:	[-], **Po**wer generation ratio
Δh:	[kJ/kg], difference of enthalpy
Δq:	[kJ/kg V.], different in specific consumption of energy between theory- and real-drying process
η	[%], the efficiency
λ:	[-], Air/fuel ratio
σ:	[-], CHP coefficient

Indices

0, 1, 2 … 6	Point 0, point 1, point 2… point 6
cal.:	Calculation
dr:	Dry
dr_1, dr_2:	Drying system1, drying system2
DS:	Dry solids
e:	The output (exit) parameters
EC:	Energy Conversion
EX:	Exhaust
FB:	Fluidized-bed-combustor
FP:	Feed-water pump
G:	Generator
H:	Heat
h:	humid
i:	The input parameters
I:	Used for the first drying system
II:	Used for the second drying system
mech:	Mechanical
P:	Particle
Po:	Power
RC:	Recirculation
St:	Steam
T:	Turbine
th:	Thermal
theor.:	Theoretical
V:	Vapour

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