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A Software for Process Assessment of Geothermal Industry and its Applications

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ABSTRACT

Software which finds application in the field of thermal process engineering in the geothermal industry has been developed. It has been devised to be easy to use and quick in providing answers and solutions during feasibility studies, process assessment, and performance cycle monitoring of condensing geothermal plants. It features a graphical interface which allows the process representation by means of a flow diagram; due to the modular conception, processes of almost any complexity may be successfully simulated.

The equations governing the thermal balance are simultaneously solved via a Newton-Raphson technique. The software also performs availability analysis (exergetic balance) and for can therefore be considered a valuable tool for educational purposes.

A few applications to the geothermal industry are illustrated and the benefits of preheating the working fluid of a geothermal plant by a renewable, low rank fuel, such as biomass are discussed.

1. INTRODUCTION

A variety of software tools for steady state analysis of thermal processes have been developed but these find limited application in the geothermal industry because these often ignore the working fluids particular to the geothermal industry. Geothermal fluids often have two or three components and generally feature two phases. The fluid that perhaps drives the majority of geothermal processes is a mixture of water and non condensable gases and this particular geothermal fluid is that considered by the software. Moreover, it takes into account other process fluids as for instance pure water, carbon dioxide, water-ammonia, ideal gases and various refrigerants.

A modular building concept has been adopted which allows the user to build up the process with broad flexibility. Each module represents an elementary process, such as compression, expansion, mixing, etc. and it is called hereinafter component.

There are 25 components available; besides those specific to processing geothermal fluids there are components of common use in process engineering. For example a number of different heat exchangers, boiler, combustion chamber etc., and few fictitious components sometimes necessary for calculation purposes.

The performance of each component is defined by a few parameters; their number has been kept as low as possible; thus, for instance, the parameters of a turbine component are: expansion ratio (or outlet pressure), isentropic efficiency, mechanical efficiency. The Mixing Condenser component features one single parameter i.e. the gas to cold water temperature approach at condenser outlet. Pressure drops or air intake can be modeled introducing appropriate components (Valve, Mixer, Source) upstream and downstream the inlet/outlet gates.

2. SOFTWARE ARCHITECTURE

The software has a graphical user interface (GUI) and the thermal balance equations are solved by a solver written in Fortran. Through the GUI the process flow diagram may be drawn and the parameters can be set; in addition the results generated by the Fortran solver may be accessed.

Figure 1 shows the forms for entering the process parameters of a couple of components.

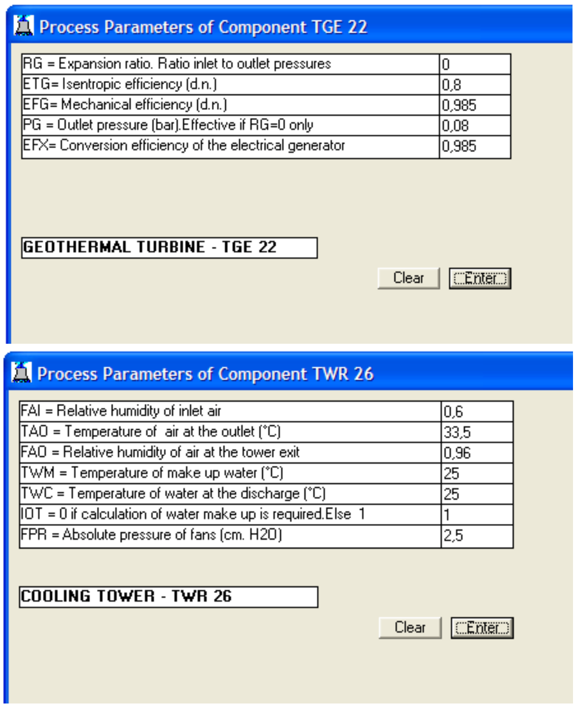

Figure 1: Forms used to enter process parameters of Geothermal Turbine and Cooling Tower components.

The GUI also interfaces with ancillary software procedures aimed at fluid property calculation and graphical representation of results.

The GUI looks like the classical Microsoft© interfaces of well known office automation software products. Below the menu bar lies the graphic area where the user accesses and drags the icons representing the process components. Connecting the components is a simple and fast operation performed by the sequential clicking of upstream and downstream gates of connected components. The connection is represented by a broken line generated in an automatic way and can be customized.

2.1 The Fortran Solver

The basic concept governing the solving procedure of thermal (mass & energy) balance follows. The relationship

$$\overline{X}_k = F_i\left(\overline{X}_j\right) \tag{1}$$

exists for each component *i* and its connections. Here $\overline{X}_k$ is a vector of fluid properties in the connection *k* downstream of component *i*, $\overline{X}_j$ is a vector of fluid properties in the connection *j* upstream of component *i* and F_i is a transfer function for component *i*.

The set of all the relationships above is a system of non linear equations that may be solved by standard methods of numerical analysis. The adopted approach is the well known Newton-Raphson algorithm which is well suited for automatic procedures. It is a recursive algorithm which entails the necessity of calculating an approximate initial value of fluid properties in each connection. This has been done using topological sorting of process components starting from those representing the fluid feeds. Then, following the ordering of each sort carried out, equation (1) is solved. If the procedure fails to calculate properties of a connection, and this occurs when the graph representing the process features nested cycles, a suitable fictitious fluid feed must be introduced somewhere in process flow diagram.

The procedure so far depicted is the initialization of the Newton-Raphson algorithm which provides an approximate value $\overline{X}^*_k$ of fluid properties in the generic connection *k*. Implementation of the algorithm leads to a solution of a system of linear equations

$$\sum_j \sum_m \left.\frac{\partial F_i}{\partial X_{jm}}\right|_* \Delta X_{jm} = X^*_{kl} - F_i\left(X^*_{jm}\right) \tag{2}$$

Where the unknown ΔX_{jm} are the corrections to X^*_{jm} and the indexes *m* and *l* indicates the elements of vectors *k* and *j*.

The matrix of the system of equations is made by the partial derivatives of transfer function of generic component *i* against variables representing the thermodynamic properties of fluid at its inlet gates; it is normally sparse and ill conditioned.

2.2 Fluid Properties

For pure water or in general for a single component fluid, properties are calculated by interpolation over a given numerical table, for the mixture of gas and pure water, i.e. the geothermal fluid taken into account, the calculation procedure follows the approach proposed by Berta and Lanzafame (1991).

The gas is assumed ideal; given that partial pressures of gas and steam of geothermal fluids are relatively low, the Dalton law is applicable and gas solubility in water may be neglected.

Fluid enthalpy and entropy are given by the relationships:

$$h = \chi_g h_g + (1-\chi_g)h_v \tag{3}$$

$$s = \chi_g s_g + (1-\chi_g)s_v \tag{4}$$

and their calculation requires the knowledge of temperature and partial pressures; the latter are calculated solving the system of equations

$$\chi_g v_g = (1-\chi_g)v_v \tag{5}$$

$$P = p_v + p_g \tag{6}$$

which leads to the following equation (7) in the unknown p_v.

$$\frac{\chi_g}{1-\chi_g} \times \frac{RT}{M_g} = (p - p_v)v_v(p_v, T) \tag{7}$$

Equation (5) states that gas and steam fill up same volume. Whenever p_v from (7) turns out higher than saturation pressure of steam at temperature *T*, then the fluid is two phase i.e. $p_v = p_{vs}$, equation (5) becomes:

$$\chi_g v_g(p_g, T) = (1-\chi_g)\chi_v v_{vs}(p_{vs}, T) \tag{8}$$

and steam quality χ_v may be calculated.

Properties of other fluids are calculated by standard methods or taken from the literature. We mention briefly that properties of water-ammonia mixture are calculated according to Ziegler and Trepp (1984) and Ibrahim and Klein (1993) and phase equilibrium is determined by equating the chemical potential of both phases of each mixture component.

3. SIMULATING THE PROCESS OF A GEOTHERMAL PLANT

The conceptual flow diagram of a typical small size (10-20 MW) condensing geothermal plant fed by superheated geothermal fluid is represented in Figure 2. The diagram is derived from the scheme reported by Dal Secco (1979).

The fluid feed is represented by component SRC 9 while the excess water discharge is represented by component SNK 32. The exhaust gas is discharged into the atmosphere via component SNK 25.

The label FSR represents a fluid feed not defined by the user but calculated in order to match the process performance of relative component.

The process features a three stage inter-refrigerated gas extractor with anti surge control valves.

The components SRC 29 and SRC 54 are dummy fluid feeds and have been introduced for calculation purposes only. They give the appropriate feeding during the initialization phase of the Newton-Raphson procedure as mentioned in Section 2.

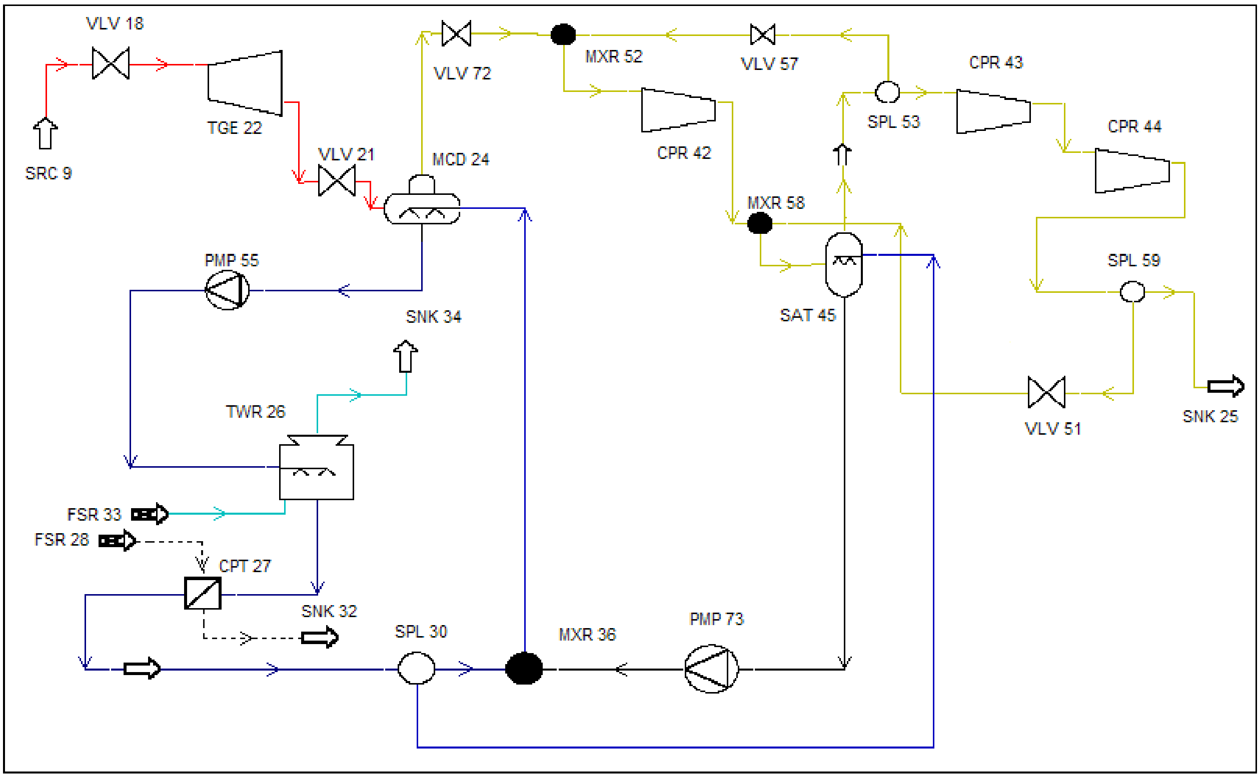

Figure 2: Basic flow diagram of a geothermal plant adopted in vapor dominated fields. Figure has been generated using the graphical interface.

Component MCD 24 is a mixing condenser while component SAT 45 is a counter current gas refrigerator. TWR 26 is an induced draft cooling tower.

The process fluid is a mixture of gas and steam at dew point with the following properties:

Flow rate = 30.56 kg/s

Pressure = 5 bar

Temperature = 155 °C

Gas mass fraction = 0.04(CO_2 = 0.95 b.w., N_2 = 0.05 b.w.)

The fluid expansion in the turbine is modeled as a single stage process with an overall mean isentropic efficiency of 0.80 which appears consistent with operating conditions. Other process parameters are:

Condenser pressure = 0.08 bar; Cold water : temperature = 25°C, flow-rate = 5500 m^3/h; Gas to cold water temperature approach at condenser outlet = 3°C, Cooling tower: range = 10 °C, approach = 5.5 °C; Extractor train: three stages with compressor ratios: 3.4, 2.1, 2.2, isentropic efficiency 0.75 per stage and gas recirculation through anti surge control valves. Environment at 25°C, 60% relative humidity (Twb=19.5°C).

A more realistic simulation can be done introducing several TGE components in cascade, as many as the turbine stages.

The results generated can be accessed selecting the component or the connection. On selecting the component the fluid properties, including exergy, at inlet/outlet connections are displayed. In addition, a few parameters summarizing the component performance are displayed.

It is worthwhile, for the considerations that will follow in Section 5 below, to report the main results of thermal balance. These are:

Shaft power = 14.500 kW

Auxiliaries = 1.383 kW

Net electric power = 12.900 kW

Inlet fluid enthalpy = 2.659 kJ/kg

Turbine outlet:
steam quality = 0.87; fluid enthalpy = 2.178 kJ/kg

The process performance is obviously affected by the atmospheric conditions. In a real plant the net power output is also strongly affected by the anti surge control valves of gas extraction train.

Gas flow recirculation in the process above was 30% through VLV 57 and 10% through VLV 51. Under ideal conditions, i.e. no gas recirculation, the extractor power consumption would be reduced by about 100 kW.

4. PERFORMANCE MONITORING OF A GEOTHERMAL CONDENSING PLANT

As already mentioned process performances are affected by atmospheric conditions. The software may be used to assess the off design performance calculating the theoretical condensing pressure which should turn out from installed equipment and from the atmospheric conditions.

It is assumed that design conditions and characteristic curves for the cooling tower and compressor train are available. The key point is the calculation of performance of the cooling tower in off-design conditions. This has been carried out adopting the Merkel theory for the given tower. Figure 3 shows the comparison between calculated cold water values with those provided by the tower manufacturer at variable atmospheric conditions.

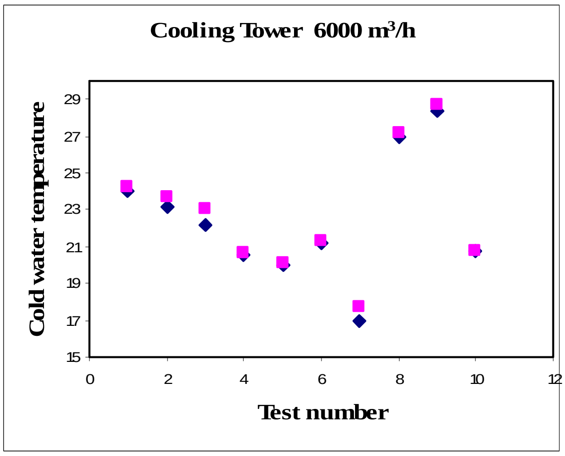

Figure 3: Comparison between calculated and design values of cold water temperature of cooling tower.

The characteristic curve of the extractor train, i.e. the relationship between the pressure ratio and the mass flow at the inlet can be approximated, by a neighboring working point, i.e. by a low degree polynomial, that for sake of simplicity, we assume of 1st degree.

Thus, pressure at the compressor inlet is assumed to be given by:

$$P_c = \frac{P_{atm}}{(k - \alpha G)} \qquad (9)$$

In (9) k and α are constants; the mass flow G depends on the pressure inside the condenser and this can be easily calculated thanks to the calculation mode CYCLE, which allows recursive thermal balance calculation with a variable parameter. The mass flow G, to be extracted from the condenser, obviously depends on the atmospheric conditions.

Figure 4 shows mass flow G vs. condenser pressure at various atmospheric conditions. Equation (9) is graphed on the same figure. The theoretical condenser pressure is thus given by the intersection of the compressor curve with the condenser curve for the atmospheric conditions on site. Data used for generating Figure 4 does not refer to the process described so far, but it has been calculated with reference to a 30 kg/s fluid flow at 200°C, 5.5 bar with 2% of non condensable gas which undergoes an expansion down to the condenser pressure. The gas to cold water temperature at the condenser outlet has been fixed at 2°C.

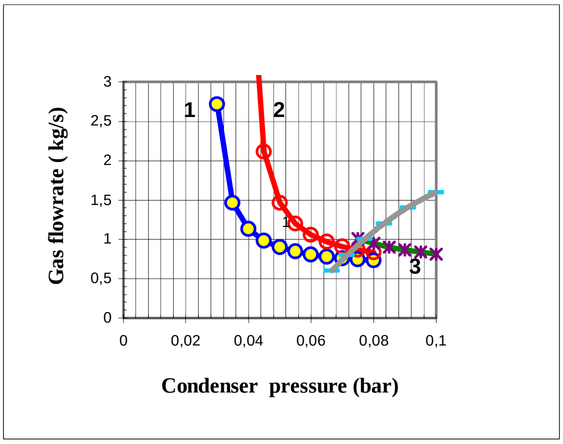

Figure 4: Flow rate to be extracted from condenser vs. condensing pressure. Curves 1, 2, 3 refer to the following atmospheric conditions: (1) Twb=11,3°C - (2) Twb=21°C - (3) Twb=25,5°C. The fourth curve is the characteristic curve of the extractor train.

It may be seen in Figure 4 that a significant variation of steam saturated gas needs to be extracted when the wet bulb temperature of ambient air changes.

The theoretical condensing pressure calculated so far is the reference value that should be compared to the actual condenser performance and any important deviation would deserve control of operation of relevant equipments.

5. IMPROVING PLANT PERFORMANCE

Due to the low temperature of geothermal fluids, compared to temperature of working fluid of a thermal plant, the efficiency of a geothermal plant is normally low.

In the past it has been proposed by Kestin et al. (1978) that the geothermal fluid be superheated by means of the chemical energy of a fossil fuel and novel thermodynamic cycles have been assessed. In those studies it was proposed to superheat the geothermal fluid up to the typical temperature (≈540°C) of a coal thermoelectric plant. At such a high temperature the thermal cycle turns out very complex, i.e. if high efficiency it is to be attained.

Using coal or other fossil fuels does not make sense at much lower superheating because the resulting thermal efficiency turns out lower that that obtainable with such fuels alone in a properly designed thermal plant. Nevertheless, as first pointed out by Neri F. (1998) a less enhanced superheating with a low rank fuel, like biomass or municipal waste, would be effective and beneficial for the geothermal plant. As can be understood, intuitively, the fluid expansion curve in the turbine is shifted towards, or entirely into, the dry steam region. These circumstances will increase the thermodynamic turbine efficiency, will reduce the erosion phenomena due to water droplets and will also mitigate and possibly avoid corrosion phenomena which originate in presence of a liquid phase in the turbine. References are made to Reinman (2000) and to Culivicchi et al.(2000).

Superheating the geothermal fluid considered in Section 3 up to 370 °C, the expansion curve through a turbine lies in the dry steam region and attains saturated conditions at turbine outlet.

This value guarantees safe working conditions of current geothermal turbine materials.

According to the Baumann rule we may assume the isentropic efficiency of turbine as the relevant value for dry steam and reasonably the value of 0.85. Reference is made to Soltani-Hosseini et al.(2000).

The super heater introduces some pressure loss and therefore fluid pressure is reduced to 4.5 bar when fluid is superheated. Under this assumption the following process performances result:

Shaft power = 19.610 kW

Auxiliaries = 1.430 kW

Net electric power = 17.900 kW

Fluid enthalpy at inlet = 3.104 kJ/kg

Turbine outlet: steam quality = 0.99; enthalpy = 2.452 kJ/kg

The heat rejection rate of the cooling tower increases from 65 to 72 MW, i.e. about 10%, that means that the same tower can be reasonably used.

The shaft power increases by 5 MW due to combined action of better thermodynamic cycle efficiency and better isentropic efficiency of the turbine; the improvement of this last part contributes by itself about 1 MW.

Calculations have been carried out also at intermediate temperatures and Figure 5 shows how shaft power increases as a function of temperature.

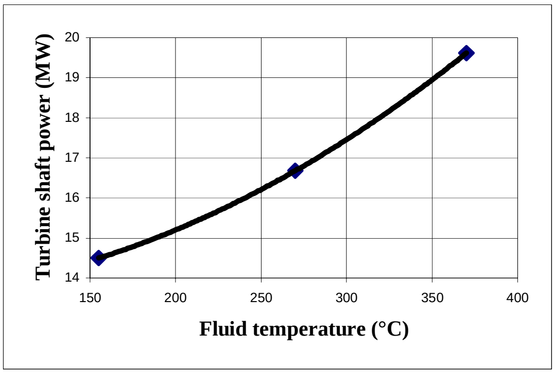

Figure 5: Power at turbine shaft as a function of fluid temperature

Comparing the results above it turns out that superheating the original fluid up to 370 °C, the expected increase of net electric power amounts to 5 MW which is about 1/3 of the original power.

The superheating process performance using woody biomass as fuel has been assessed according to the scheme in Figure 6. The fuel features a low calorific value (LHV) of 10.600 kJ/kg at 35 % moisture content. To control ash melting, combustion temperature is kept as low as about 1000 °C, re-circulating 20% of flue gas. Flue gas is cooled down to about 160 °C in the air pre-heater. Under these conditions the calculated thermal efficiency is about 85% and the power input, given by the fuel, is 16 MW. The estimated auxiliary consumption is 200 kW.

In conclusion the superheating process proposed may give a net electric power increase of 4.8 MW using a thermal input of 16 MW, thus the marginal net efficiency is 30%, which is a fair amount higher than that of conventional power plants fed by biomass.

6. CONCLUSIONS

A software program for process studies in the geothermal industry has been presented. Moreover, the concept of superheating the working fluid of a geothermal power plant, using woody biomass as fuel, has been illustrated and the studies carried out, thanks to this software, have been discussed. Biomass is a fuel already used for power generation; biomass plants adopt steam Rankine cycle and feature conversion efficiency below 30%. In the last decade many studies, aimed at increasing conversion efficiency of biomass power plants, led to the proposal of the Integrated Gasification Combined Cycle that, in a unique application in Europe, was expected to reach 29% efficiency, according to Morris and Waldheim (2002).

The superheating concept proposed here, despites the low temperature, allows attaining comparable conversion efficiency with much less complicated technology and capital investment.

In addition geothermal superheating is effective for mitigating turbine blade erosion due to water droplets and corrosion produced by chloride contaminants in a wet environment.

As a consequence of natural flow decline of a geothermal resource, during exploitation, the power generated by the installed plants will be lower than the rated power; under these circumstances the superheating proposed here may be a valid concept for implementation.

NOMENCLATURE

$h =$ Specific enthalpy

$s =$ Specific entropy

$\chi =$ Mass fraction

$v =$ Specific volume

$P =$ Pressure

$p =$ Partial pressure

$R =$ Gas constant

$T =$ Temperature

$M =$ Molecular weight

Subscripts

$g =$ gas

$v =$ steam

$vs =$ steam at saturation

$c =$ condenser

$atm =$ atmospheric

$wb =$ wet bulb

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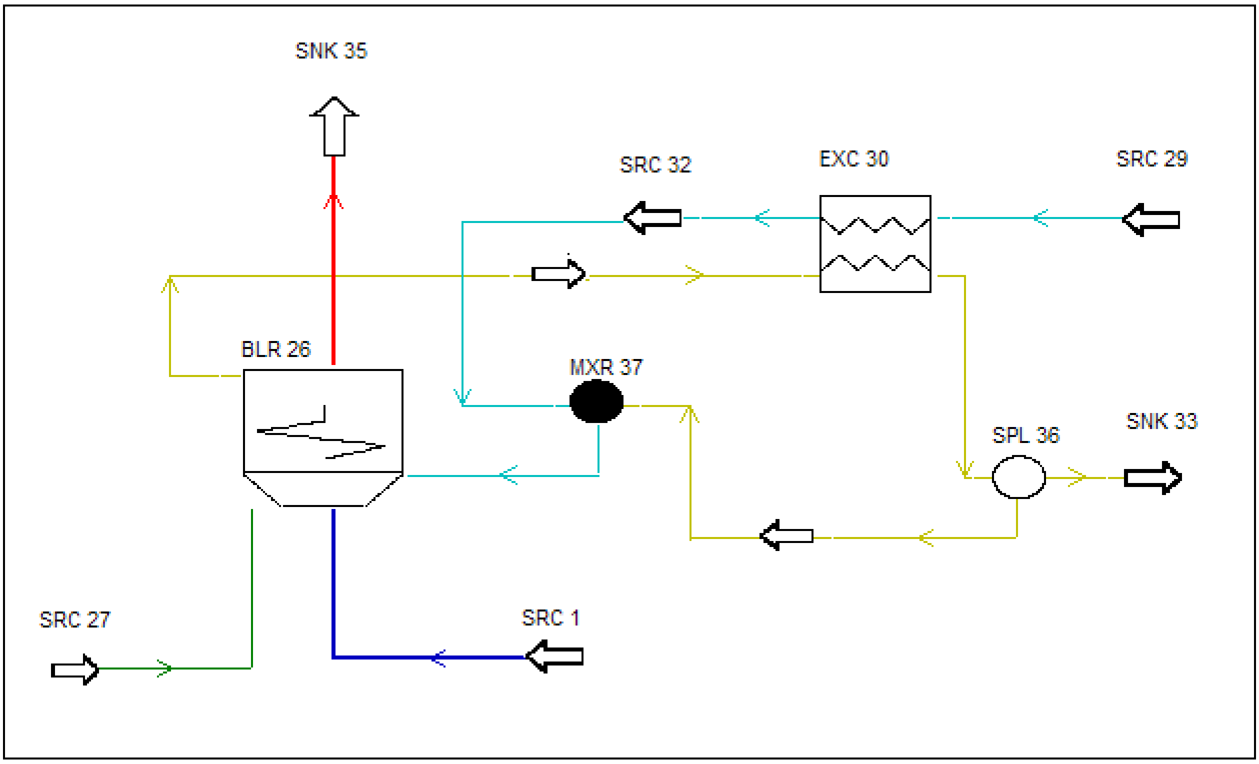

. Figure 6: Flow diagram of superheating process using biomass. Flue gas recirculation is introduced to control combustion temperature.