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DEVELOPMENT OF A POLYGENERATION DISTRICT HEATING AND COOLING SYSTEM BASED ON GASIFICATION OF RDF

Natalia Kabalina1,2, Mário Costa1 and Viktoria Martin2
1 IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
2 Kungliga Tekniska Högskolan, Stockholm, Sweden
E-mail: natalia.kabalina@ist.utl.pt

ABSTRACT
A polygeneration district heating and cooling (DHC) system may produce not only cold, heat and electricity but also added-value product(s) depending on the technology selected. A promising choice as energy source for a polygeneration DHC system is refused derived fuels (RDF). RDF can be transformed into a useful fuel (syngas) through gasification, which originates added-value products. The syngas can be used as the main fuel for the combined heat and power system, and the solid products may originate important added-value products, such as char coal. The main objective of this study is to examine the potential of using RDF as the main fuel for the polygeneration DHC system. To this end, thermodynamic, exergy and economic models were developed and applied to the proposed system. The results reveal the technical and economical potential of using RDF in polygeneration systems.

INTRODUCTION AND STATE-OF-ART
A district heating and cooling (DHC) system comprises a combined heat and power generation plant, distribution networks (heat and cold) and consumers (households, municipal buildings, etc.). Such a system provides thermal comfort to final costumers, and it is rather important in countries with cold winters, though it may be also suitable for countries with the relatively moderate climate as well. The conventional DHC system consumes considerable amounts of fossil fuels. This unfavorable consumption might be reduced by upgrading the conventional DHC system to a polygeneration DHC [1], [2]. The polygeneration system relies on different energy sources, including renewables. In this case, the DHC polygeneration system may produce not only cold, heat and electricity but also added-value product(s) depending on the technology selected.

A promising choice as energy source for a polygeneration system is refuse derived fuels (RDF). Basically, the term “RDF” stands for a wide variety of comparatively high calorific products derived from municipal solid waste (MSW). Until very recently the common practice for the MSW utilization was landfilling with or without a pre-step of incineration. Recently, the European Union introduced regulations (Directives 2006/12/EC and 1999/31/EC) to restrict the solid waste landfilling with the goal to utilize MSW with the minimal impact on the environment and to intensify energy/resource recovery. One option is to process the MSW in order to obtain RDF, which can be used as either raw material or fuel.

Biomass, which includes the RDF, might be transformed into a useful fuel through two major processes: thermo-chemical or biological (anaerobic digestion and post-composting) [3]. The thermo-chemical treatment includes processes such as combustion, pyrolysis, gasification and direct liquefaction. Of those, the pyrolysis and the gasification present a great potential to be used in polygeneration DHC systems, while the liquefaction process is currently too complex and expensive to be a suitable solution. The combustion of biomass is the oldest and the most prevalent method of the biomass conversion [4], though its use in DHC polygeneration systems may limit the manufacturing of added-value products. Of the technologies listed above, gasification seems to be the most promising since it originates a syngas (CO2, CO, H2, CH4 and others), and solid products (char and tar) [4]. Thus, the syngas can be used as the main fuel for the combined heat and power (CHP) system, and the solid products may be regarded as important added-value products. For example, the formed char coal could be used as a partial substitution of raw CaCO3 in the cement industry [5] or as fuel for energy generation [6].

The main objective of this study is to examine the potential of using RDF as the main fuel of the polygeneration DHC system. Studies on RDF applications to polygeneration district heating and cooling systems are very scarce in the literature. The proposed system should be able to provide heat/cold and electricity for a region of Lisbon, called EXPO, and added-value products. The RDF conversion process used here is the gasification technology, which yields a syngas along with added-value products (char coal).

METHODOLOGY
The proposed DHC polygeneration system was designed based on an existing one; specifically, the Climaspaço DHC system, located in Freguesia of Santa Maria dos Olivais, Lisboa. This unit is a trigeneration system with a CHP working on natural gas with cold and heat distribution networks 60 km long [7]. The CHP output data were obtained from the Climaspaço unit, and the proposed DHC polygeneration system scheme includes the following major units: a gasifier, a gas turbine, a boiler, and an absorption chiller. Fig. 1 shows a schematic of the proposed DHC polygeneration system.

To evaluate the performance of the present system thermodynamic, exergy and economic models were developed in EES (Energy Equations Software) environment, which includes a detailed database of thermochemical properties for various substances.
Thermodynamic modeling

In order to model the system, a number of assumptions have been introduced such as:

- The system is regarded as stationary, with all processes being adiabatic and in equilibrium.
- Losses do not vary during the CHP operation so that equipment efficiencies are constant.
- The gas turbine works at the full load constantly, thus outlet exhaust gases characteristics do not change during operation.

- The system supplies heat and cold demands completely, while the electricity is produced also for selling to the grid.
- The major electricity consumers are the syngas compressor and the compression chiller.
- RDF is the main fuel and natural gas is used as the back-up fuel.

In this work the gasifier was modeled using the stoichiometric equilibrium model [4]. During the pyrolysis stage large biomass molecules disintegrate into smaller molecules of organic liquids (mostly tar), gases, char and ash without any interaction with the gasifying medium. In the gasification stage, gases and char in the presence of the oxidizer undergo through several major reactions, which determine the final syngas composition. Desrosiers [8], as it was reported by [9], indicated that, within gasification temperature range (600 K to 1500 K), CO$_2$, CO, H$_2$, CH$_4$, H$_2$O and char are the only products that exist with concentrations higher than 10$^{-4}$ mol%. Assumptions similar to those listed in [9], [10] were also applied here.

According to [11] the typical gasification temperatures for RDF are within 1073 K and 1173 K; in this temperature range the following reactions are common [4]:

C + CO$_2$ ↔ 2CO  
C + H$_2$O ↔ CO + H$_2$  
C + 2H$_2$ ↔ CH$_4$  
CO + H$_2$O ↔ CO$_2$ + H$_2$

Equilibrium constants for reactions (3) and (4) may be found in references [12] and [13], as it was stated by [14]. In addition, it was assumed that char is pure carbon with mole ratio yield equal to 0.04.
An energy balance to the gasifier can be written as:

\[ LHV_{RDF} \times m_{RDF} + q_{\text{H2O}} + q_{\text{air}} + q_{\text{ext}} = q_{\text{syn}} + q_{\text{char}} + q_{\text{losses}} + q_{\text{gas}} + q_{\text{ash}} \]  

(5)

where the value of LHV of RDF was taken from reference [15].

The thermal energy of the gases was calculated through the expressions given in reference [16].

In Eq. (5), \( q_{\text{gas}} \) represents the net heat, which needs to be delivered/diverted to/from the reactor and can be calculated as follows [25]:

\[ q_{\text{gas}} = \Delta H_{T,R} = \Delta H_{298}^{0} + \sum_{j=1}^{\text{n}} x_{j} \Delta H_{f}^{0,j} \]  

(6)

where the RDF heat of formation can be calculated as [17]:

\[ \Delta H_{298}^{0} = LHV_{RDF} + \frac{1}{m_{RDF}} \sum_{j=1}^{\text{n}} x_{j} \Delta H_{f}^{0,j} \]  

(7)

The remaining enthalpies of formation were obtained from [18].

The modeling of the gas turbine, boiler, absorption and compression chillers and others minor units was performed based on existing equipment. Table 1 presents the characteristics of these units.

### Exergy modeling

The main drawback of the first law analysis is that it characterizes different energy flows (heat, cold and electricity in the present study) as equal without taking into account their quality and their real potential towards the reference system. In addition, for the system balance it does not allow to consider the material flows (charcoal and syngas in the present study) as energy carriers. These shortcomings might be overcome by the exergy analysis. For this analysis the following assumptions were introduced:

- the system is quasi-equilibrium;
- the reference model does not undergo through changes in time;
- all gases behave ideally;
- kinetic and potential exergy changes are negligible.

The exergy balance for the polygeneration DHC system could be written as:

\[ E_{RDF} = E_{\text{syngas}} + E_{\text{char}} + E_{\text{exhaust}} + E_{w} + E_{\text{heat}} + E_{\text{cold}} + E_{\text{ash}} + E_{r} \]  

(8)

and the chemical exergy of RDF (organic part) might be calculated as follows [25]:

\[ e_{RDF \text{org ch}} = \beta \times LHV_{RDF} \]  

(9)

### Economic modeling

The economic evaluation of the system performance was based on the discounted net cash net flows criteria [26]:

\[ NCF = \sum_{i} \frac{C_{F}}{(1+i)^{i}} \]  

(10)

The cash flow for each year (in USD), with the exception of the first year, consists of annual revenues from electricity, heat, cold, syngas and char coal sales with the substraction of the annual expenditures (maintenance, operation and insurance). Costs such as consumables were excluded from the model.

### Table 1. Characteristics of the proposed units.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameter</th>
<th>Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>Polytropic efficiency</td>
<td>80%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Mechanical efficiency</td>
<td>97%</td>
<td>-</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>Exhaust temperature</td>
<td>783 K</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td>Engine efficiency</td>
<td>31.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output power</td>
<td>5670 kW</td>
<td></td>
</tr>
<tr>
<td>HRSG</td>
<td>HRSG outlet temperature</td>
<td>421.95 K</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>HRSG efficiency</td>
<td>67.1%</td>
<td>[21]</td>
</tr>
<tr>
<td></td>
<td>Steam pressure</td>
<td>10 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steam temperature</td>
<td>473 K</td>
<td></td>
</tr>
<tr>
<td>Absorption chiller</td>
<td>COP</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Compress-ion chiller</td>
<td>COP</td>
<td>5.25</td>
<td></td>
</tr>
<tr>
<td>Conventional cyclone</td>
<td>Collection efficiency</td>
<td>90%</td>
<td>[22]</td>
</tr>
<tr>
<td></td>
<td>Pressure drop</td>
<td>10 kPA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature drop</td>
<td>10 K</td>
<td></td>
</tr>
<tr>
<td>Air-to-water heat exchanger</td>
<td>Efficiency</td>
<td>90%</td>
<td>[23]</td>
</tr>
<tr>
<td></td>
<td>Pressure drop</td>
<td>5 mbar</td>
<td></td>
</tr>
<tr>
<td>Venture scrubber</td>
<td>Collection efficiency</td>
<td>100%</td>
<td>[24]</td>
</tr>
<tr>
<td></td>
<td>Pressure drop</td>
<td>0.5 mbar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Working temperature</td>
<td>303 K</td>
<td></td>
</tr>
</tbody>
</table>

The net cash flow for the first year has also investment costs. Furthermore, all costs associated with district
heating/cooling networks and installation, civil and project engineering are excluded from this model since the proposed plant is intended to be constructed on the existing site.

The equipment costs were estimated following the method proposed in references [27] - [29]. The costs were updated to the level of the 2013 inflation by means of the chemical engineering plant cost index (CEPCI) [30]:

\[ \text{Inf} = \frac{\text{CEPCI}_{2013}}{\text{CEPCI}_{\text{year}}} \]  

(11)

The project lifetime is assumed to be 20 years in agreement to the lifetime of a typical CHP plant working on natural gas.

The fuel price is a crucial parameter for the economical model establishment. According to reference [31] prices of RDF vary from 0 to 40 euro/ton. Moreover, it should be stressed that currently there is no well-established market for RDF.

RESULTS

Thermodynamic analysis

According to reference [32], RDF specifications depend highly on the production line scheme and their origin. In the present study the RDF characteristics were taken from reference [33]. Table 2 shows a comparison between the predicted syngas composition with the present model and that obtained from experiments [33].

Table 2. Comparison between predicted syngas composition with the present model and that obtained from experiments [33].

<table>
<thead>
<tr>
<th>Volatile gas</th>
<th>Content (%v)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>H₂</td>
<td>42.6</td>
</tr>
<tr>
<td>CO</td>
<td>14.5</td>
</tr>
<tr>
<td>CO₂</td>
<td>9.2</td>
</tr>
<tr>
<td>CH₄</td>
<td>2.0</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>-</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>-</td>
</tr>
<tr>
<td>H₂O</td>
<td>31.5</td>
</tr>
<tr>
<td>N₂</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Despite the model predicts well the contents of H₂ and CO, it fails to predict accurately the contents of CO₂, CH₄ and H₂O. These deviations can be attributed to a number of factors, namely, syngas composition assumed in the model and char content assumed at the output of gasifier.

As syngas LHV is significantly lower than the natural gas LHV, the syngas mass flow rate fed to the GT must increase in order to produce the same electricity output at the generator terminals. As a consequence, the flue gases flow rate from the syngas combustion increase significantly as compared with the natural gas combustion, which causes an increase in the steam generation capacity.

The thermodynamic study reveals that the produced amount of steam in the proposed system covers completely the required head load, unlike the current system installed at Climaespaço. Additionally, the steam produced by the proposed system is enough to supply the absorption chiller so that less than 0.001% had to be provided by the compression chiller. Moreover, for the maximum heat and cold production the proposed system is produces steam in excess that can be used for other purposes.

It should be noted that the annual thermodynamic trigeneration efficiency varies marginally with the gasification temperature.

Exergy analysis

Fig. 2 shows the annual exergetic efficiency as a function of the steam to carbon ratio at a gasification temperature of 1073 K. It is seen that the exergetic efficiency augments as the S/C ratio increases. Although the syngas LHV decreases with S/C ratio for a given ER due to incomplete combustion, its decline results in higher mass flow through the GT and HRSG and, consequently, in higher cold fraction generated in the absorption chiller with the same thermal input.

It is interesting to note that an increase in the ER leads to a similar result, that is, a growth in the exergy efficiency due to the related reasons.

![Fig. 2. Annual exergetic efficiency as a function of the steam to carbon ratio at a gasification temperature of 1073 K.](image_url)

Economic analysis

Table 3 presents the key results of the economic analysis and optimization.

A parametric study carried out revealed that within the considered RDF price range, the net cash flow and the discounted cash flow for the first year are not sensitive to price changes. Fig. 3 shows the net cash flow as a function of the syngas produced for selling. It is observed that the increase of the syngas for selling results in lower payback periods along with growth of the net cash flow for 20 years.

![Fig. 3. Net cash flow as a function of the syngas produced for selling.](image_url)
Table 3. Key results of the economic analysis and optimization.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average exergy efficiency</td>
<td>0.62</td>
</tr>
<tr>
<td>Annual average trigeneration efficiency</td>
<td>0.76</td>
</tr>
<tr>
<td>Annual average cogeneration efficiency</td>
<td>0.46</td>
</tr>
<tr>
<td>Net cash flow for 20 years, mln USD</td>
<td>318.4</td>
</tr>
<tr>
<td>Revenue char, mln USD</td>
<td>0.03</td>
</tr>
<tr>
<td>Revenue syngas, mln USD</td>
<td>28.3</td>
</tr>
<tr>
<td>Payback period, years</td>
<td>2</td>
</tr>
</tbody>
</table>

**OUTLOOK**

Further investigation will include refining of the present models and detailed validation against experimental data. Moreover, the knowledge of the impact of the RDF heterogeneous characteristics on the gasifier performance has to be carefully evaluated. To this end, the design and construction of a laboratory RDF gasifier will be considered.

**CONCLUSIONS**

This work examined the potential of using RDF as the main fuel, instead of natural gas, in a polygeneration DHC system in Lisboa, Portugal. To this end, thermodynamic, exergy and economic models were developed and applied to the proposed system. The results revealed that the full replacement of natural gas by RDF is technically and economically feasible. The new fuel is relatively cheap and yields relatively low payback periods for the project implementation. Complimentary added-value products such as syngas and char coal brings additional profit to the system, almost doubling the net cash flow. Furthermore, the proposed system reduces the impact of MSW on the environment and allows recovering energy from it. Finally, the system provides final customers with energy without direct carbon emissions.

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