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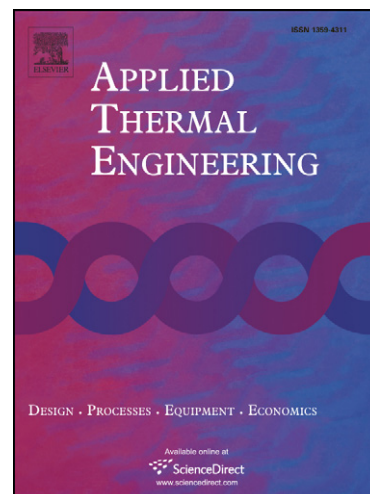
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Heat Integrated Heat Pumping for Biomass Gasification Processing

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Abstract

The main part of this paper is an industrial case study. It deals with an application of a heat pump in energy systems for biomass gasification in a wood processing plant. Process Integration methodology is applied to deal with complex design interactions as many streams requiring heating and cooling are involved in the energy recovery. A refrigeration cycle maintains low temperature in the scrubber where the production gas (or synthesis gas – syngas) is cooled and undesirable contaminants are removed before the syngas is introduced into the engine. In addition to electricity generation, a large amount of waste heat is available in the biomass gasification system studied in the paper, and its appropriate heat integration with utility systems within a plant allows the available heat to be efficiently utilized for the site. The conceptual understanding gained from the case study provides systematic design guidelines for further process development and industrial implementation in practice

Keywords

Biomass Gasification, Wood Drying, Heat Pump, Heat Integration, Grand Composite Curve

1 Introduction

The world today can be characterized by increasing interest in renewable sources of energy. Utilizing renewable sources of energy, especially biomass is one of the priorities of the EU energy policy. The amount of biomass used for energy production in the EU rises every year by about 2 % to 3 % [1]. It is expected that in the future the growth will be much higher. The following Table 1 provides an estimate of potential for biomass-related development in the EU up to 2030. In the future energy crops will play a dominant role in the biomass market.

However, nowadays, forestry and waste processing residues prevail in energy production process. The biomass can be transformed into useful energy by different processes [2]. One of the most wide-spread processes is combustion. The state-of-the art of biomass combustion technologies has been described in many monographs [3]. Production of “green” power is strongly supported within the EU to achieve an increase in the contribution of renewable energy sources to electricity production [5]. Besides exploitation of biomass for heating purposes, we can expect growth in the number of applications where power is generated. Traditional technologies for combined heat and power production from biomass are based on the conventional Rankine cycle with water/steam involved as working fluid. Technologies involving the Organic Rankine cycle [6], where the silicon oil as a working medium is used instead of water/steam have become commercially available.

Generally, the efficiency of electricity production is quite low in a mid-sized unit fired by biomass compared to the performance of conventional power plants. A comparison of performance of three different conversion processes (i.e. combustion, gasification and pyrolysis) for biomass-based power generation has been published for example in [7]. Gasification with subsequent utilization of syngas produced in an engine represents an interesting alternative to biomass combustion. Technological principles and advantages of this process are described in detail in [8]. To secure failure free operation it is necessary to provide the required quality of the syngas before it is fed into the engine or turbine. Typical concentrations of particulate matter and tars at fixed bed gasifier outlet have been reported in range $100 - 8,000 \text{ mg/m}_N^3$ for particulate matter and $20 - 15,0000 \text{ mg/m}_N^3$ for tars [9]. These contaminants if introduced into the engine cause fouling on both its static and moving parts of the internal combustion chamber and intake manifold. Requirements on quality of gaseous fuel set by internal combustion engine manufacturers to guarantee long-life failure-free operation are as follows: (i) Particulate matter lower than 50 mg/m_N^3 ; (ii) Tars content should not exceed 100 mg/m_N^3 [9] .

There are many techniques available for the removal of undesired contaminants [9]. One of the most commonly used methods is wet scrubbing [10]. It is mostly useful for the mechanical separation of dust. Simultaneously tarry compounds are condensed and removed from the syngas. The lower the temperature in the units is, the higher efficiency can be expected. Practically achievable temperature is close to 0 °C., if water is used as the circulating medium. This leads to a refrigeration cycle in which heat removed from the process stream has to be pumped to a higher temperature level.

Fig. 1 displays a layout of the gasification technology, designed for utilisation of the syngas in a cogeneration unit. The syngas leaving Cyclone 3 is first cooled in a Recuperative Heat Exchanger 4, serving for air preheating. After that, it is cooled in a Heat Exchanger 5 down to about 330 °C and coarse particulate matter is collected in a Filter 6. Further cooling of the syngas down to a temperature of near 0 °C has to be performed by direct contact of the syngas with a cooling medium.. The syngas is also cleaned from the tar substances during the direct cooling.. They are condensed and collected (scrubbed) by the cooling medium. Water is considered as the cooling/scrubbing medium.. Besides electricity a large amount of waste heat is produced within the unit by the engine as well as by the heat pump (HP). This heat should be effectively utilized to improve energy management of the plant.

2 Methodology

The strategic and integrated matching of available heating/cooling resources in the processes, with heat rejection to/from the HP systems is able to significantly enhance thermal efficiency and cost-effectiveness for the whole process when a HP is applied as a means of producing high-grade heat from low-grade or waste heat. A major challenge in the design of HP systems comes from the complexity of energy integration. The design of HP system is highly

interactive and interlinked to the processes. In industrial applications the process often consists of several streams to be cooled or heated to the required levels of temperature. This heating and cooling demand from individual streams could be merged and represented by Grand composite curves (GCC) [11, 12, 13]. They show the collective characteristics of heating and cooling information of the whole system. Information obtained from the GCC is then used for synthesis of utility systems [14, 15, 16]. Process Integration techniques can then be applied to determine the most appropriate use of HP leading to significant energy savings. It is necessary to screen available heating and cooling sources of the process from the GCC [17, 18]. This investigation provides the information about appropriate cooling (heating) level(s) and corresponding sizing of HP (or heat duty). Fig. 2 illustrates how the HP is conceptually designed. From the shape of the GCC, it would be better to have two levels (Levels 1 and 2) for removing a heat from the process streams, rather than one level at Level 2, in terms of external power (W) required to drive the HP. From the information given by the GCC, the levels for heat rejection to process streams (Q_{HP+W}) and heat removal from the process (Q_{HP}) can be determined systematically. This close matching between HP and GCC provides significant benefits for the design and application of a HP in an industrial context.

The effect of a systematically integrated HP on utility requirements (most often this is steam and cooling water - CW)) is demonstrated in Fig. 3. Heat supplied by hot utilities (Q_{Hmin}) as well as low-grade heat (Q_{Cmin}) rejected to cold utilities is decreased.

An industrial case study for biomass gasification is given to demonstrate the applicability of the heat-integrated design methodology for the applications of HPs. For the biomass gasification process considered in the case study, there is a potential to utilise waste heat from the process with an improved energy management. Two scenarios are considered to exploit the application of the HP system:

- i) Utilisation of a HP for heating the water for wood drying, and

i) Utilisation of a HP for boiler feed-water preheating.

Significant potential for energy saving is envisaged by the appropriate placement of the HP with the process using the GCC concept.

3 Wood processing plant – mass balance and heat requirements

Wood processing is accompanied by a large amount of wooden-waste produced on the one hand and high energy intensity on the other hand. General data about primary wood processing can be found e.g. in [19]. Let us consider the following material flow. From each 1000 m³ processed in the plant, only one half forms a desired product – timber. The rest turns into waste material which composes of sawdust (approximately 15 %) and lump waste wood (remaining 35 %). The main product – timber commonly requires drying before it undergoes downstream processing. Wood drying to achieve its desired humidity is a long-lasting batch process, which takes part in a drying kiln. The length of the cycle depends on many factors. The most important are inlet and target water content; the woody species dried, and last but not least the drying technology available. There are many types of dryer modifications used in this field. They differ by the way of heat transfer to the material:

- Drying by hot air: The air is heated by a hot water loop or by steam. This is the most common method.
- Drying with superheated steam: This represents a very effective process modification. The time required for drying is considerably reduced and the quality of timber treated is preserved at the same time.

These two methods have been studied in detail by various authors (e.g. [21, 22]). When superheated steam is used, drying times are reduced several times: Drying of spruce board in superheated steam takes about 1 day, while in the case of hot air 60 to 90 h cycle is expected.

Regardless of method applied, the drying process is intensive in terms of heat consumption. For example, 1 MW of energy is typically necessary for the heating of drying air which is required for 264 m³ of the daily production of timber as comes from real industrial facility. As a hot utility, steam is typically used for supplying heat to the kiln. Steam is produced in a biomass-fired boiler. Based on simple calculation of energy balances, the fuel consumption of 12.5 t of wooden waste per day can be predicted. This amount is equivalent to approximately a half of the daily production of wooden waste. The fuel is produced on-site, so fuel cost can be assumed negligible. The rest of unused fuel is sold to third parties. Typically, no power is produced in this configuration.

The idea presented in this case study aims at achieving efficient exploitation of waste wood produced within the plant, leading to better energy management for the plant. The solution analysed in this paper is based on the successful and cost-effective integration of the gasification reactor pictured on Fig.1 with the existing boiler. The aim of this work is to find and evaluate a solution with waste heat utilization, which covers the demand for heat for drying and simultaneously produces green electricity. As has been mentioned previously syngas cleaning system with cooling of circulating scrubbing medium represents an integral part of such technology. The integration of a HP is considered to utilise low-grade heat more effectively as well as to ensure high energy efficiency for the overall energy systems. Both of the drying methods are analysed in terms of their possibility for effective HP integration.

4 Heat pump for water heating: drying with hot air

Let us consider a heat supply system for the first option, in which heat recovered from gasification unit (i.e. heat rejected by Heat Exchanger 5, Low-Grade Heat Scrubber 7 and hot water produced in Engine 9 in Fig. 1) is utilized for hot water production. The application of HP assumes the installation of a new loop where the circulated water used as a utility is first

preheated by the heat rejected by HP, and then its temperature is raised to target temperature from process heat recovery and additional heating from the existing boiler. From this heat recovery, the system of gasification unit shown in Fig. 1 and hot water circuit can be considered together, and their corresponding energy and mass balances are performed to obtain inputs for data extraction procedure. The following process parameters are identified in the system of interest:

- 550°C** - Syngas temperature at the gasifier outlet
- 3°C** - Target temperature to which the syngas is cooled. The syngas has to be cooled down to the temperature close to 0°C, when problematic tarry compounds contained in the syngas are condensed and subsequently separated from the syngas.
- 330°C** - Above this temperature we are in a “safe area“, where no tarry compound condensation occurs and thus no fouling problem can be expected. A conventional heat exchanger can be applied to cool the raw syngas. Below this temperature fouling problems are significant.
- 40°C** - Clean syngas, before storing in a tank, is heated to the temperature well above its dew point.
- 90°C** - Target temperature of hot water covering dryer requirements on heat of 1 MW.

Based on those operating conditions, data extraction for the flowsheet is made. Stream data (i.e. hot and cold streams extracted, their supply and target temperatures and enthalpy change) are summarized in Fig. 4. The data for stream C3 is based on the requirement of hot water (i.e. 8.48 t/h at 90 °C). Total requirement for the heating of drying air (i.e. 1 MW as mentioned in Chapter 3) is decreased by the waste heat produced in the reciprocating engine. Streams H1, H2, H3, C1, C2 and C3 are candidates for heat recovery. In the next step, a Grand composite curve is created (see Fig. 5). The calculations are performed for ΔT ranging

from 2.5 °C to 70 and the profitability is evaluated as well. The highest benefits are achieved for ΔT between 7.5°C and 12.1 °C, where the objective function representing cost savings is characterized as very flat. Moving to the lower ΔT , the effectiveness is reduced due to increased delivery costs (i.e. increased pressure drop in heat exchangers). Higher ΔT result in increased shaftwork for heat pump driving. Mean of the interval, i.e. $\Delta T = 9.8$ °C, is assumed for analysis used further in text. GCCs are used for identifying of load and level of utilities. The pocket denoted by downward arrows represents the area where heat recovery between hot and cold streams takes place. Requirement on heating and cooling are not covered by this way, but satisfied by utilities. According to Fig. 5 the process requires supply of 341 kW of heat (see the horizontal line above the Pinch point – its importance is discussed later on). Due to its temperature level this demand is covered by steam. Simultaneously it is necessary to remove 92 kW at temperature level -10 °C (see the horizontal line below the Pinch point). The GCC also reveals the scope for using a HP. If we examine carefully the GCC profile and focus on the part around the Pinch point, we can determine levels for heat rejection/removal as well as HP duty (i.e. make sizing). By following rules specified above, a HP is placed such that low-grade heat is removed from HP cycle at temperature -10 °C (Q_{HP}) and heat from condenser of the HP cycle is rejected to process stream at 35 °C ($Q_{HP} + W$).

The results show that application of the gasification unit with integrated HP provides considerable reduction for fuel requirements of boiler (Fig. 6). Only one quarter of its current capacity is required after application of process integration methodology. Saved boiler capacity can be further utilized e.g for power generation. The excess steam expands in steam turbine or the capacity of the plant can be significantly raised without the need for new boiler capacity increase.

Preliminary results reveal that the application of integrated HP is promising. Large financial benefit can be expected. However, economy of operation is strongly dependent on HP

performance. The most important factor that influences coefficient of performance (COP) is the difference between the temperature in the evaporator and the condenser (ΔT_{HP} in Fig. 7). Since the temperature level of refrigeration is fixed at $-10\text{ }^{\circ}\text{C}$, the parametric sensitivity of inlet temperature of cold stream C3 on HP performance is tested. A simple mathematical model for cost savings assessment has been prepared. It provides us with data necessary for economic assessment e.g. COP, shaftpower consumption, amount of steam saved, green power production. For the COP calculation the model assumes: (i) Ammonia is selected as a working fluid; (ii) The cycle works according to the ideal thermodynamic cycle. Results of the assessment are summarized in Table 2.

Inlet (return) temperature of stream C3 is changed from 15°C to 75°C . This causes significant change in GCC profile (Fig. 8). This is critical for achieving effective and successful HP integration. For constant amount of heat rejected by HP (Q_{HP}) increase in ΔT_{HP} is accompanied by higher compression work (W) and a corresponding decrease in COP. For the return temperature 15°C the model evaluated the COP equal to 4.3, for 75°C it was only 2.2. As a secondary effect the amount of heat available in the condenser ($Q_{HP}+W$) rises as well.

The consumption of steam is reduced approximately to one quarter of its original value. The rest of heat required for drying is supplied by waste heat from the gasification reactor, engine and HP. The first and second are constant values whereas heat rejected by the HP depends on ΔT_{HP} . It starts at 120.4 kW for minimal $\Delta T_{HP, \min} = 47\text{ }^{\circ}\text{C}$ and rises to 169.4 kW for maximal $\Delta T_{HP, \max} = 98\text{ }^{\circ}\text{C}$ (see Fig. 7). If there are now 12.5 t of wooden waste per day introduced into the boiler, its total consumption of waste wood increases to 20.2 t/d as follows from the material balance of the suggested system. This is because all fuel saved in the boiler and some extra waste wood is combusted in the reactor. Since there is still an excess of waste wood produced within the plant (30 t/d) no additional biomass has to be purchased. The technology, however, produces a significant amount of green power, which if exported, ensures a large

economic profit (see Table 2). Actual output of existing biomass boiler can be significantly reduced, according to decrease of steam consumption or it can be fixed and excess of steam effectively utilized for additional power production. Expected engine power output is 454 kW, of which 28 to 77 kW (depending on ΔT) is consumed in HP. Green power production efficiency within this system exceeds 20 %, which is high value compared to efficiencies achievable by other means of biomass-based power production in small units with capacity 1 or 2 MW. The costing saving is shown in details in Table 2.

5 Utilization of heat pump for boiler feed water preheat – drying in superheated steam

This section considers drying when superheated steam is applied. The same analysis comprising the data extraction and targeting follows. The heat and mass balances are re-adjusted as the energy recovery is now based on steam loop. In the second step, data extraction is carried out (Fig. 8). In the previous case no stream representing heat from gas engine cooling has been included. Heat produced by engine (258 kW) has been subtracted from total requirements (1 MW) and the difference has been represented by C3 (i.e. enthalpy change 742 kW). Once the steam loop is considered this a simplification is not possible. It is due to higher quality of heat for covering plant demand compared to the temperature level of heat available from engine cooling. An additional stream H4 representing available heat from gas engine cooling is added (compare Fig.4 and 8). Total requirements on steam generation are described by streams C3, C4, C5 and C6 (C3 – make-up preheating, C4 – condensate preheating, C5 boiler feed water heating to saturation temperature, C6- steam generation).

One of the interesting design parameters which influence the efficiency of the steam system as well total requirements on make-up (C3) and condensate preheating (C4) is the rate of condensate returned to the boiler house. In these calculations, 20 % condensate return is

assumed. A large amount of steam is directly used up in the drying kiln without condensate recovery and a certain amount of condensate is lost. With data shown in Fig. 8 we can get the GCC with changed profile. Examination of the profile revealed that in this case there is no space for effective HP integration. This is caused due to the large amount of heat available from gas engine cooling (H4) compared to the requirements of cold streams. We can conclude, that this is not suitable for HP integration if heat rejected by HP is utilized for boiler feed water preheat when syngas combustion takes place in a reciprocating engine. The replacement of the reciprocating engine with a small gas turbine is considered. Compared to the engine, all the heat produced in the turbine is concentrated into the flue gas flow at higher temperature level [23]. As in the previous case there is not much potential for energy savings if practically acceptable ΔT of HP is desired to avoid large compression work. The condensate return ratio does not affect the performance too much.

6 Conclusion

The presented case study demonstrates that significant energy savings can be achieved through the strategic use of a heat pump applied in the unit for biomass gasification. The refrigeration cycle provides conditions for extensive syngas cleaning before it is introduced into the combustion engine. The power output of the engine is 454 kW. The efficiency of power generation exceeds 20 %. Most of the waste heat is utilized for covering plant demand on drying air heating through strategic use of heat pump. Process Integration methodology provides conceptual insights for the design of heat pump since it is integrated with complex processes involving many streams requiring heating and cooling. The Grand Composite Curve provides beneficial information for sizing of a heat pump cycle (heat removed by heat pump is 92.4 kW) and determination the most appropriate levels of heat rejection/removal in a heat pump. An attention has been paid to heat-integrated HP to ensure the cost-effectiveness of HP applications since the shaft power can vary significantly - from 28 to 77 kW - for different operation condition. In some cases - boiler feed water preheating - the potential for

energy savings is very low and practically unacceptable temperature difference of heat pump is observed and large compression work is unavoidable.

Acknowledgement

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References

- [1] European Environmental Agency: Supply, transformation, consumption- renewables and wastes, annual data, 2005, [online], <www.epp.eurostat.ec.europa.eu> (19.2.2009)
- [2] D. L. Klass, Biomass for Renewable Energy, Fuels and Chemicals, Academic Press, San Diego, 1998
- [3] S Loo van., J. Koppejan, Handbook of Biomass Combustion and Co-Firing, Twente University Press, ISBN 9036517737, 2002.
- [4] EC, Communication from the Commission. Biomass Action Plan, COM (2005) 628, Brussels, 7.12.2005
- [5] European Parliament and the Council. Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market. Official Journal of the European Communities 2001; L283:33-40
- [6] Ch. Wu, Thermodynamic cycles. Computer-aided design and optimization, Marcel Dekker Inc., New York, 2004
- [7] A. V. Bridgwater, A. J. Toft, J. G. Brammer, A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion, Renewable and Sustainable Energy Reviews, (6) 2003, 181-246.

- [8] J. Rezaian, N.P. Cheremisinoff, Gasification technologies. A primer for engineers and Scientists, CRC Press, Taylor & Francis Group, Boca Raton, 2005.
- [9] P. Hasler and T. Nussbaumer, Gas cleaning for IC engine applications from fixed bed biomass gasification, Biomass and Bioenergy, 16 (1999), 385-395
- [10] A. Bartocci, Syngas Cleaning System Using Wet Scrubber Technology, In: Proceedings of the Twenty-seventh Annual International Conference on Thermal Treatment Technologies, Session A8, Air & Waste Management Association, Montreal, Quebec, May 12-16, 2008.
- [11] B. Linnhoff, D. W. Townsend, D. Boland, G. F. Hewitt, B. E. A. Thomas, A. R. Guy, R. H. Marsland, User Guide on Process Integration for the Efficient Use of Energy; IChemE: Rugby, England, 1982, last edition 1994.
- [12] CPI (Centre for Process Integration). Heat integration and energy systems. MSc Course, School of Engineering and Analytical Science, The University of Manchester, UK, 2004/2005.
- [13] R. Smith, Chemical Process Design and Integration, John Wiley & Sons, Ltd, Chichester, England, 2005.
- [14] J.-K. Kim, R. Smith, Cooling water system design, Chemical Engineering Science, 56 (2001), 3641–3658.
- [15] P. O. Kapustenko, L. M. Ulyev, S. A. Boldyryev, A. O. Garev, Integration of a heat pump into the heat supply system of a cheese production plant, Energy, 33 (2008), 882-889
- [16] T. Zhelev, The conceptual design approach—A process integration approach on the move, Resources, Conservation and Recycling, 50 (2007), 143-157

- [17] R. Nordman, T. Berntsson, Use of advanced composite curves for assessing cost-effective HEN retrofit I: Theory and concepts, *Applied Thermal Engineering*, 29 (2009), 275-281
- [18] R. Nordman, T. Berntsson, Use of advanced composite curves for assessing cost-effective HEN retrofit II: Case studies, *Applied Thermal Engineering*, 29 (2009), 282-289
- [19] J.C.F. Walker, *Primary Wood Processing: Principles and Practice*, 2nd edition, Springer, 2007.
- [20] E. Tsotsas, A.S. Mujumdar (eds.): *Modern drying technology*, Volume 1: *Computational Tools at Different Scales*, John Wiley & Sons, Ltd., 2007,
- [21] A. Johansson, Ch. Fyhr, A. Rasmuson, High temperature convective drying of wood chips with air and superheated steam. *International Journal of Heat and Mass Transfer*, 40 (1997), 2843-2858.
- [22] N. Petchers, *Combined heating, cooling & power handbook*: The Fairmont Press, Inc., Lilburn, 2003.

Figure Captions

Fig. 1 An example of technology for biomass gasification with production of thermal energy and power

Fig. 2 Using Grand composite curve for the integration of heat pump (after [12])

Fig. 3 Effect of integrated HP on utility requirements (after [12])

Fig. 4 Extracted streams marked within overall flowsheet (I)

Fig. 5 Grand composite curve, requirements on utility and HP integration principle

Fig. 6 Grand composite curve, requirements on utility after HP integration

Fig. 7 Effect of increasing return temperature of C3 on HP Integration

Fig. 8 Extracted streams marked within overall flowsheet (II)

Fig. 1 An example of technology for biomass gasification with production of thermal energy and power

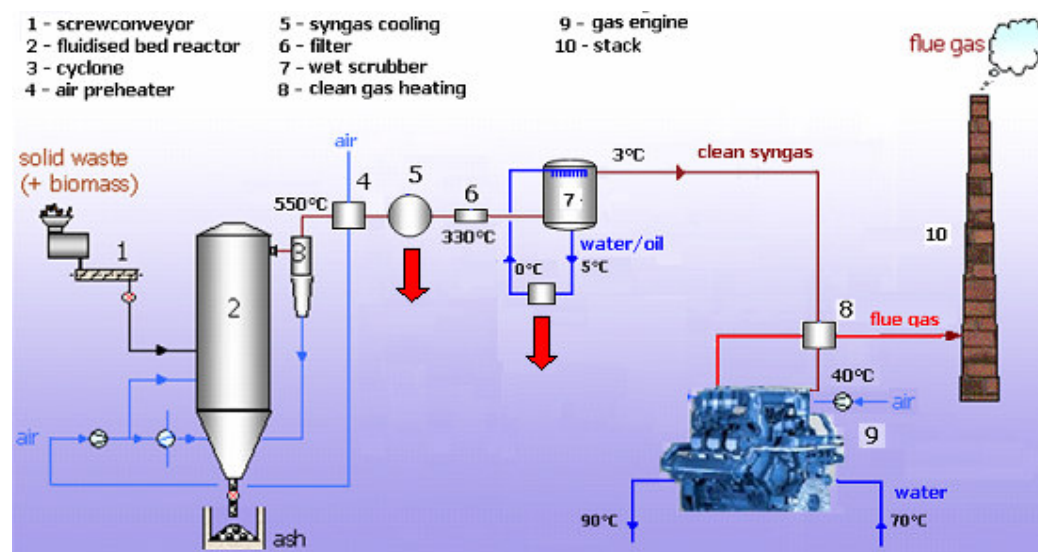


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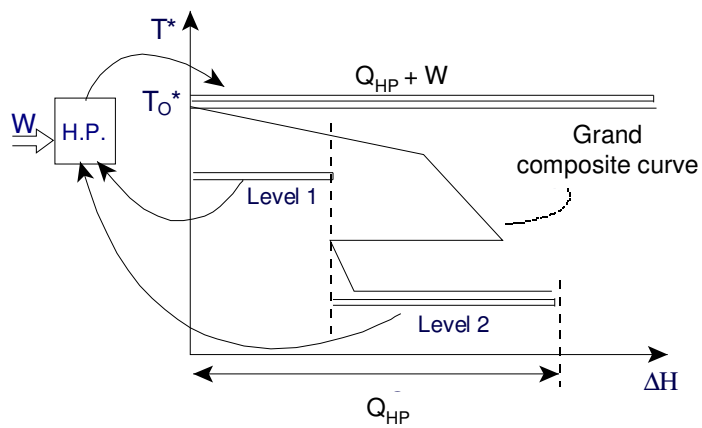


Fig. 3 Effect of integrated HP on utility requirements (after [12])

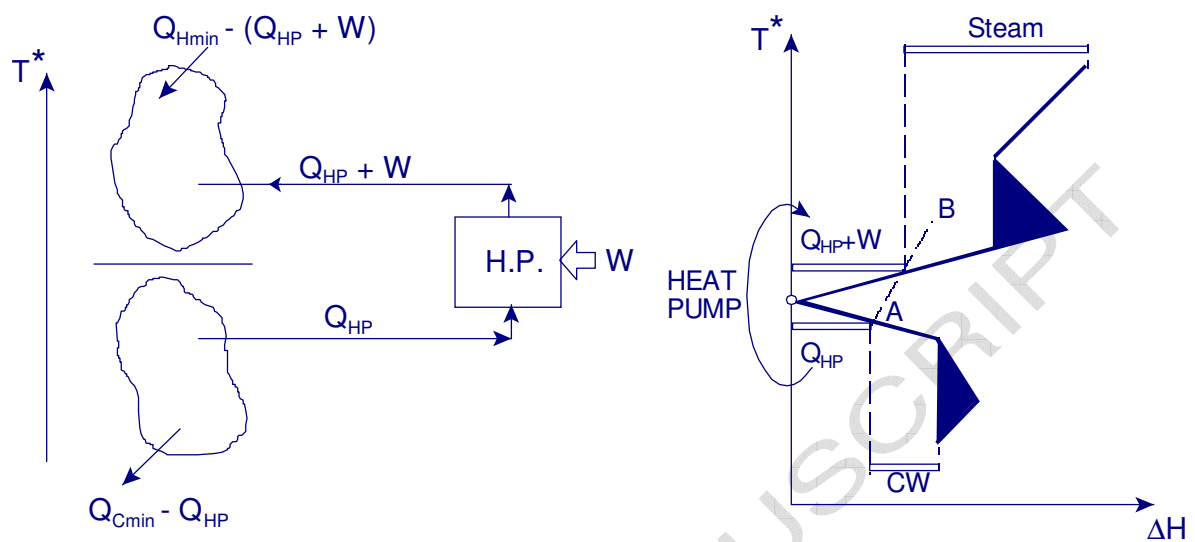


Fig. 4 Extracted streams marked within overall flowsheet (I)

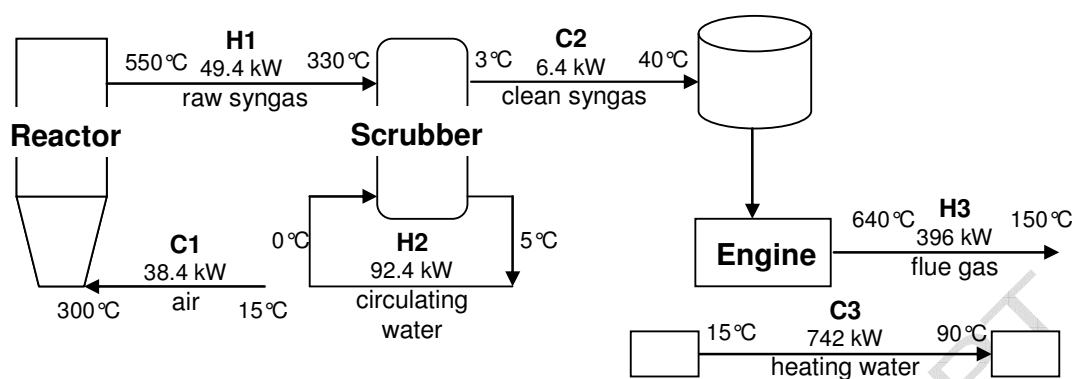


Fig. 5 Grand composite curve, requirements on utility and HP integration principle

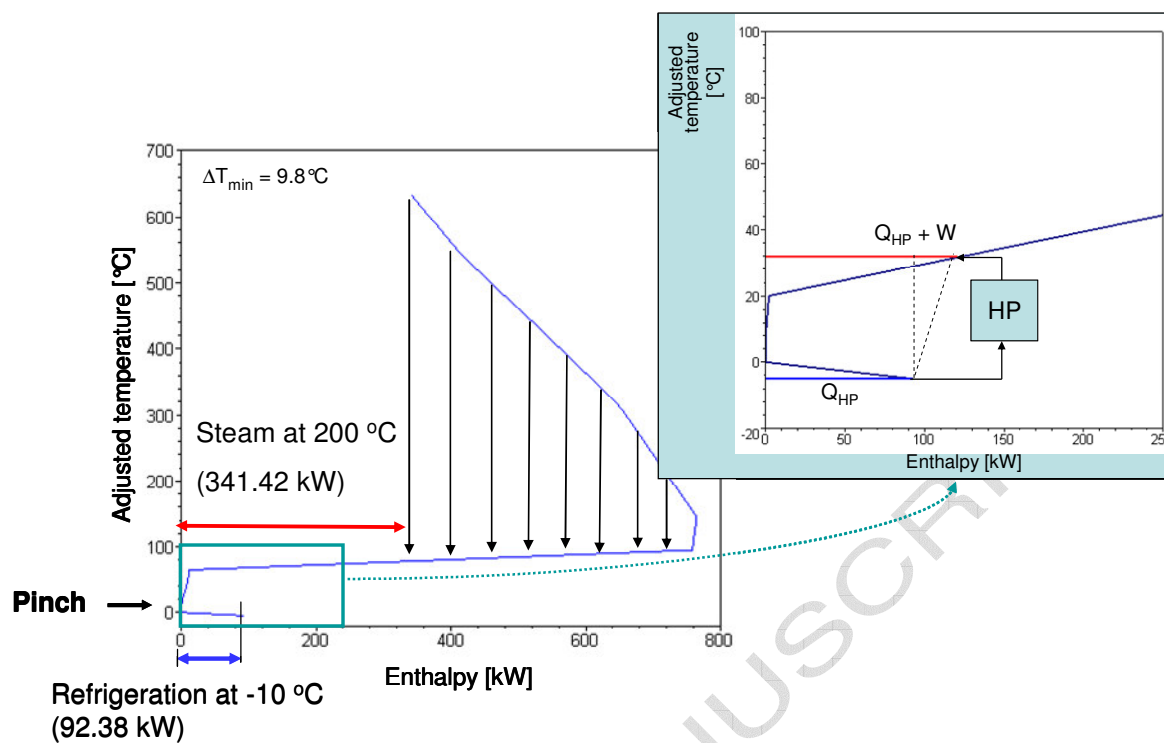


Fig. 6 Grand composite curve, requirements on utility after HP integration

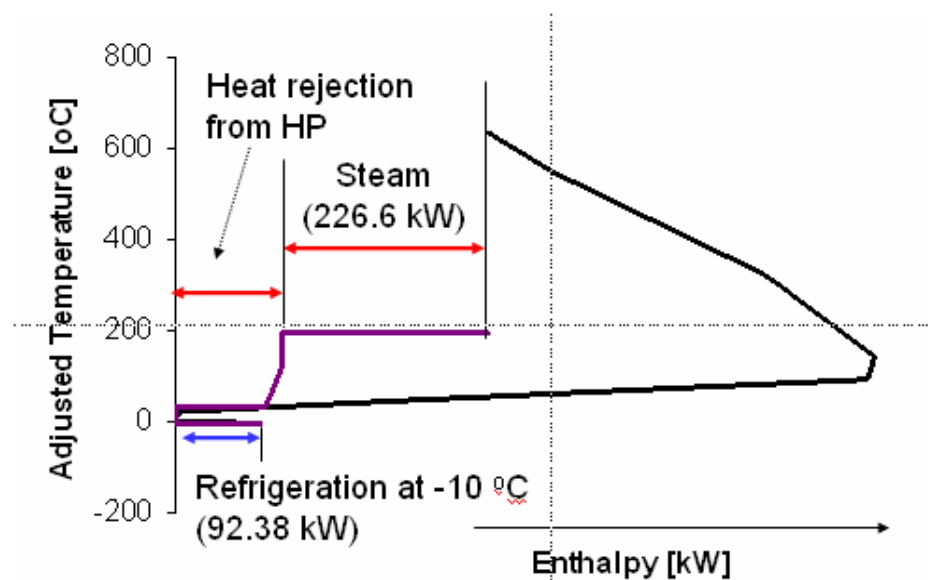


Fig. 7 Effect of increasing return temperature of C3 on HP Integration

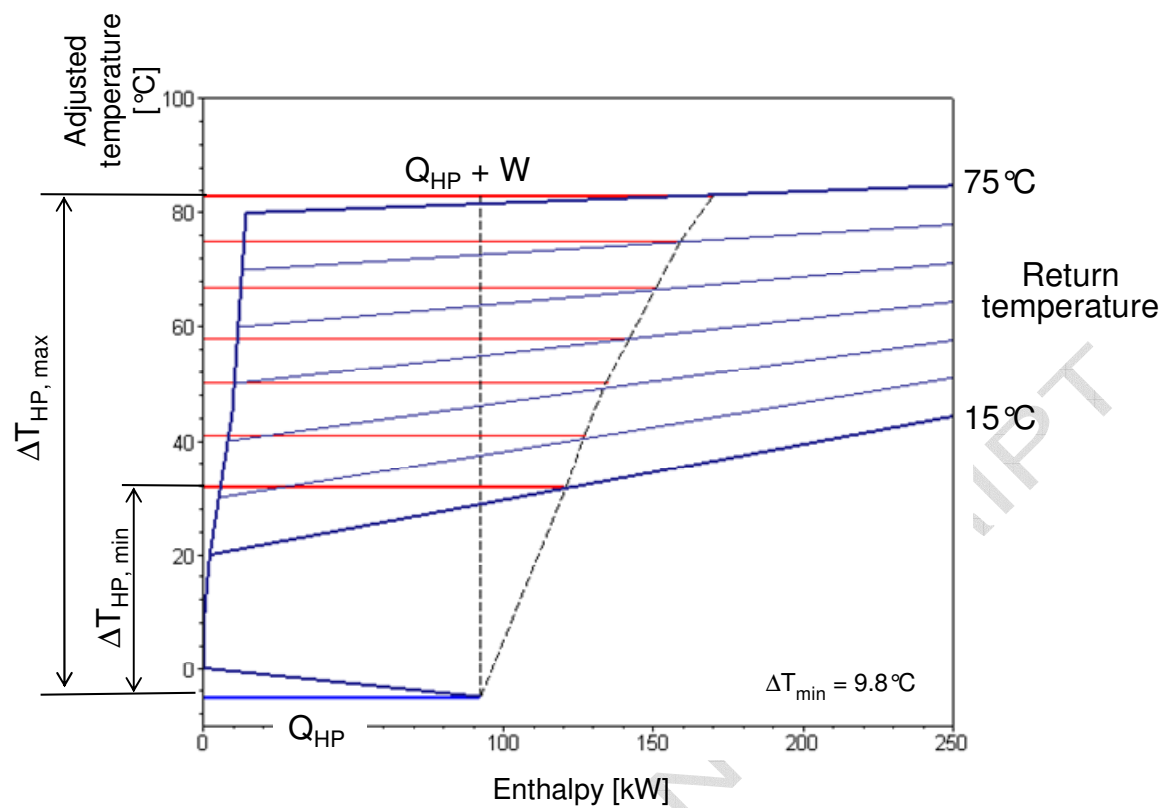


Fig. 8 Extracted streams marked within overall flowsheet (II)

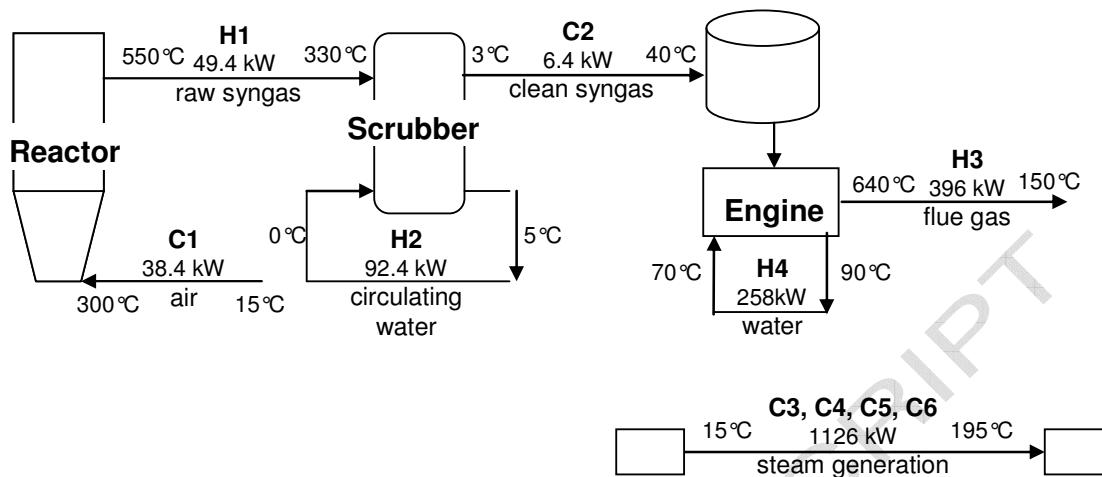


Table Captions

Table 1 Estimated development of biomass potential in EU 25 in Mtoe (*toe = ton of oil equivalent, 1 toe = 41,868 GJ*) [1].

Table 2 COP analysis and Cost saving assessment

Table 1 Estimated development of biomass potential in EU in Mtoe (toe = ton of oil equivalent, 1 toe = 41,868 GJ) [1].

Biomass source	Biomass potential		
	2010	2020	2030
Forestry residues	43	39 - 45	39 - 72
Organic waste from wood processing, agricultural production and food industry	100	100	102
Energy crops	43 - 46	76 - 94	102 - 147
Total	186 - 189	215 - 239	243 - 316

Table 2 COP analysis and Cost saving assessment

$T_{C3\text{return}}$	[°C]	15	25	35	45	55	65	75
ΔT_{HP}	[°C]	47	56	65	73	82	90	98
Biomass Sale	[k\$/yr]	-112	-111	-109	-108	-106	-105	-103
Power Export	[k\$/yr]	417	410	403	396	387	379	369
Service Cost	[k\$/yr]	-43						
Total	[k\$/yr]	264	259	253	247	240	233	225