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A method to separate the problem of heat transfer interactions in the synthesis of thermal systems

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Abstract

Most of the efforts to improve energy system configurations are directed towards the recovery of internal heat, which reduces the contribution of the external hot source and enhance system efficiency accordingly. This problem is strictly related to the synthesis of different components into system topology, i.e. with the definition of the optimal system configuration according to specified objectives.

A new method for the optimization of the heat transfer interactions within energy systems is presented here, based on the idea of cutting thermal links between the "basic" components of the system. The boundary temperatures of hot and cold flows that are generated as a consequence of these cuts are evaluated in an optimization procedure that involves the design parameters of the system as well. The high potential of the proposed method consists in separating the problem of defining the system configuration into two separate sub-problems, the first regarding the definition of the "basic" topology of the system (related to all components different from the heat exchangers), the second the optimal heat transfer interactions within the system. This feature makes complex systems today only marginally "optimizable", amenable to complete optimization. The method is applied to a humid air turbine (HAT) cycle plant, which represents a good test to prove its reliability and generality, due to the internal recirculation of mass and energy flows.

Keywords: Optimization; Heat transfer; Synthesis

1. Introduction

The need to improve energy conversion systems performance pushes towards new and more complex configurations in which the most appropriate level of integration among components has to be achieved. The challenge for the designers is to obtain the simplest configurations to fulfill a desired objective, which is, in general, the minimum unit cost for a given amount of a product. Other objectives such as minimum environmental impact or maximum efficiency, or all these objectives together may suggest other system configurations, and/or different design parameters for the same configuration. The complexity of the resulting configuration also depends on the limits that are considered for the technological level of the components.

System configurations are usually decided by a design team on the basis of experience and creativity. Some methods were already proposed in the literature to find improved system configurations, and a brief summary is given in Section 2. The new approach suggested in this paper aims at simplifying the problem of the synthesis of the components (i.e. the definition of system configuration). The main idea consists in identifying the "basic" components of the system configuration first, and then *in cutting the thermal links between the "basic" components, so that hot and cold thermal flows are generated within the system. Inlet and outlet temperatures of the "basic" system components (which are also the boundary temperatures of these hot and cold flows) are established independently of one another as decision variables of an optimization procedure in which the other design parameters of the system are involved as well*. This approach derives from similar ideas, already presented in [1–4], where all possible heat transfers within the system were included in a black-box (see also [5]), and a

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parametric procedure for design improvement was performed by adjusting the temperatures at black-box boundaries using Pinch Technology [6] and Second Law guidelines (see, e.g., [7]).

This approach indeed separates the problem of defining the system configuration into two sub-problems: the sub-problem regarding the definition of the ''basic'' topology that comprises the ''basic'' components of the system, and the sub-problem of the optimal heat transfer interactions within the system. The first sub-problem is not treated in this paper, although some original ideas are presented in Section 3 about how ''basic'' system configurations can be viewed as the composition of one or more thermodynamic cycles involving one or more working fluids. These are meant as guidelines for future work and their aim is to introduce the approach to the solution of the second sub-problem, which is presented in Section 4. A humid air turbine (HAT) cycle plant is used as test case in Section 5 to show the capabilities of the method because of the high number of recirculating mass and energy flows.

2. The synthesis of system components in the literature

In the design of a thermal system, ''synthesis'' is concerned with putting together the separate components into the system configuration [8]: this is equivalent to specify the particular devices involved and their interconnections. In general, the process is not straightforward. A tentative system configuration is first proposed according to some criteria based on previous experience or new ideas of the design team. This configuration is analyzed to quantify system performance and feasibility, and then evaluated from the economic point of view. A design parameter optimization may be performed at this step pursuing some specified objective(s). If the results are satisfactory, a flowsheet and a detailed design are generated. Otherwise, modifications to system topology are suggested and a new configuration is created and analyzed. This iterative procedure leads to improvements of the system configuration and, in the best case, to the optimal system configuration according to the specified objective(s).

Topology changes are usually proposed on the basis of designers' experience and creativity. In fact, a standard procedures does not exist yet, although several attempts were made in the literature to include this experience into organized procedures [9]:

(i) Artificial intelligence and expert systems (see, e.g., [10,11]) were used to generate new system configurations by means of rules derived from exergy analysis. Appropriate indicators are used to evaluate and sort the different candidate configurations.

(ii) Various design criteria were obtained for heat exchanger networks by rules and heuristic principles codified in more or less organized sets of guidelines (see e.g., [6,7,12,13]). These rules were also used to improve the overall synthesis of heat and power systems [6].

(iii) Some authors proposed the optimization of the thermodynamic quantities of ''superstructures'', which include all ''possible'' configurations for a given type of system (see e.g., [14–17]). So, portions of the superstructure that are considered as unnecessary are excluded, and the ''optimal'' configuration is identified.

(iv) Design techniques based on the emulation of natural processes were recently proposed by the so-called ''constructal theory'' [18] to generate optimal flow geometry in system devices.

The limit of these criteria is that they either apply to specific components, such as heat exchangers, or do not guarantee that an optimum configuration is obtained, or both. In fact, referring to the criteria mentioned at point (i) above, the optimization of a system configuration using exergy quantities might not guarantee that the true optimum is found if the relationships between exergy quantities and the underlying thermodynamic variables (mass flow rate, pressure, temperature and chemical composition) is not taken into account correctly. On the other hand, a different heat exchanger networks design may result from the application of the different approaches mentioned at point (ii) above. For example, the highly systematic and easy-to-use approaches proposed by the Pinch Technology [6] are demonstrated to be improved using second law principles by exergy analysis [19] and further improvements can be obtained with the automatic synthesis using evolutionary algorithms (see, e.g., [20]). Moreover, the analysis of a superstructure (see point (iii)) relies on the assumption that a superstructure exists, and that we are able to define it in advance. However, an absolute criterion to generate the superstructure does not exist yet, and its level of complexity is highly subjective, being mainly dependent on designer's experience. Finally (see point (iv)), constructal theory shows a high potential of development, but it seems still early to formulate a judgment on it.

All these considerations highlight the difficulty in finding the optimal system configuration due to the combinatorial nature of the synthesis problem, which results in an explosive number of theoretically possible configurations as soon as the level of complexity grows beyond systems with few elementary devices. On the other hand, the number of actual system configurations is not so high, most of them being based on few elementary thermodynamic cycles. General guidelines for the improvement of these configurations lead towards different options. One of these consists in including new devices, such as a gasification reactor when poor fuels are used in internal combustion cycles, or saturators when the thermodynamic or environmental performance dictate the saturation of air streams with water vapor. Another option consists in integrating the existing processes with internal heat transfers or in the appropriate organization of system components.

The general problem of the overwhelming number of possible configurations can be approached by analyzing the thermodynamic cycles that are practically used in energy conversion systems, as is shown in the following section.

3. Synthesis as the composition of thermodynamic cycles

The synthesis of thermal systems configurations can be considered as an operation by which one or more thermodynamic cycles are "composed" into a single system. These cycles may be open or closed and the nature of operating fluids may be different (e.g., air/gas, water/steam, ammonia, carbon dioxide, etc.). Each cycle is made up of the four fundamentals transformations of a thermodynamic cycle (e.g., the Carnot cycle): compression, heat exchange with the high temperature source, expansion and heat exchange with the low temperature source (Fig. 1). The most common components that accomplish the four fundamental transformations are (strictly in the following order): compressor, hot source heat exchanger, expander, cold source heat exchanger. Different cycles may share common transformations when their streams are mixed into a single one and then undergo the same transformations (Fig. 2). Special secondary components such as saturators and mixers are used for this purpose. The common paths of the cycles end when the streams are separated in other special secondary components, such as separators, condensers or splitters.

An option to make cycle structure more complex is to split some components into stages (e.g., the turbine or compressor for staged expansion or compression, see Fig. 3). Another option is to add secondary heat exchangers between any couple of subsequent "basic" components. Theoretically, this operation can always be done in any cycle structure. However, it is worthless between the cold source heat exchanger and the compressor and between the hot source heat exchanger and the expander, because the presence of heat transfer devices in these points of the cycle is harmful from the thermodynamic point of view. Thus, a direct link must exist

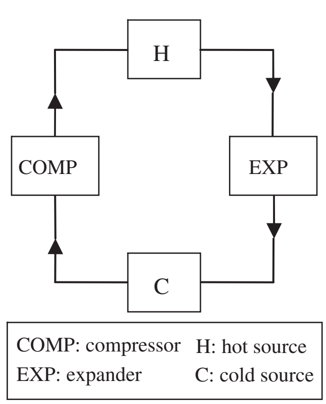


Fig. 1. Generic thermodynamic cycle.

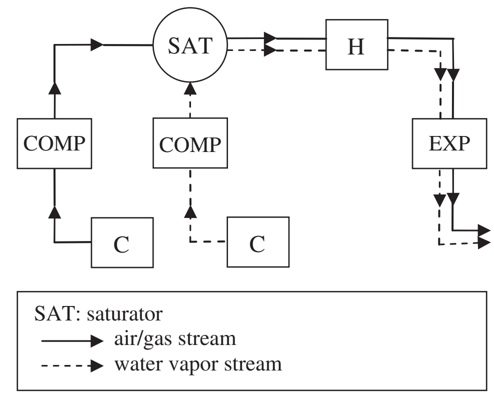


Fig. 2. Example of cycles featuring common transformations (HAT cycle).

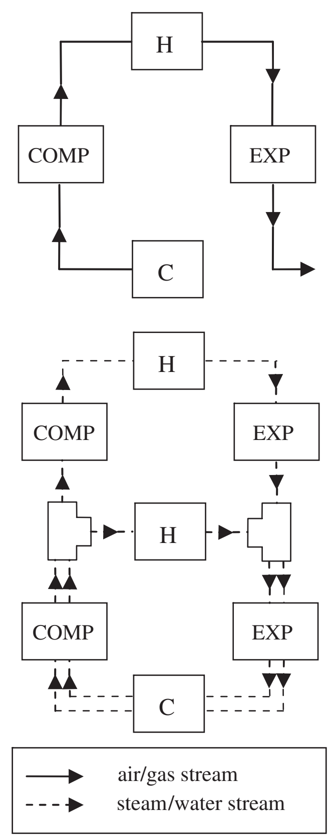


Fig. 3. Splitting of components into stages (combined cycle-two pressure levels).

between those components, independently of cycle complexity. Conversely, cycle paths can be considered as "interrupted" anywhere else (Fig. 4) to allow for the inclusion of heat transfer devices that may increase or decrease the temperature of the streams (pressure drops in these devices are not considered at this level of structural analysis). These temperature variations generate cold flows that need to be heated or hot flows that need to be cooled.

The above considerations are the basis of the method that is presented in the next section to optimize heat transfer interactions within a particular system configuration.

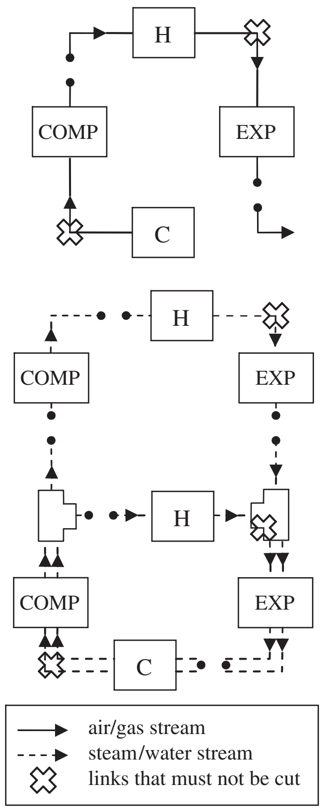


Fig. 4. Interrupted links for the inclusion of secondary heat exchangers (combined cycle—two pressure levels).

The synthesis of different configurations aimed at optimizing system topology in a general sense is beyond the scope of this paper.

4. Optimal heat transfer interactions

As it was shown in the preceding section, each cycle path within the system is defined by a sequence of ‘‘basic’’ components, and this sequence may be ‘‘interrupted’’ to take into account the option of including heat transfer devices. Starting from these concepts, the overall configuration of a given system, no matter how it is generated, can be ideally subdivided into two portions:

- The first portion includes the ‘‘basic’’ cycle components, which are ordered according to the sequences defined by cycles themselves. This portion determines the basic characteristics of the system, so in the following it is referred to as the ‘‘basic system configuration’’. Note that the problem of defining component sequences in the basic system configuration as a result of the composition of different cycles is not considered here. Referring to existing plant configurations, it appears that component sequences depend on the ‘‘concepts’’ that have inspired the considered plant. For instance, the concept of a gas–steam combined cycle implies that a Brayton–Joule and a Rankine cycle are coupled, the former on top of the latter. Each of the two cycles has a sequence of basic components that are always present and connected in the same way: a compressor, a combustion chamber and a turbine for the topping cycle, a boiler (heat recovery steam generator), a steam turbine, a condenser and a pump for the bottoming cycle. The general problem of the synthesis would require a general method to organize the cycles and the related components into the most appropriate basic structure according to the objective of the analysis. Here it is assumed that component sequences of the basic system configuration are already given.
- The second portion encloses the interruptions between components in the cycle paths, and comprises all the hot and cold thermal flows generated by these interruptions. This portion corresponds to the heat transfer section of the system.

Accordingly, this second portion of the system topology appears as a black-box inside the basic system configuration (Fig. 5). Within the black-box, the heat exchanger network that accomplishes all the heat transfers is still unknown at this step of the analysis, and the definition of its topology is another separated sub-problem that can be solved only after all heat transfers have been quantified (in fact, the temperature at the boundaries of the black-box are still to be established).

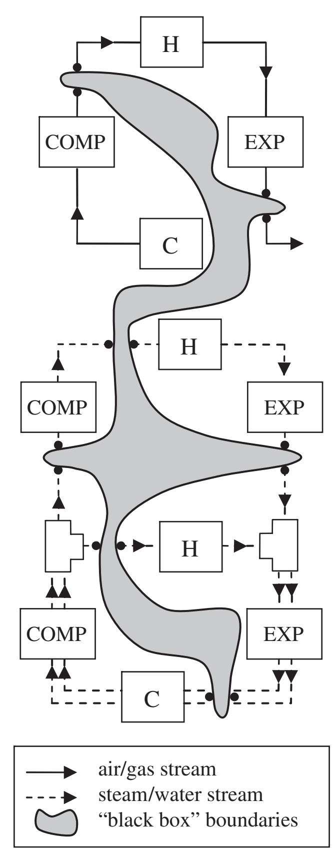


Fig. 5. Basic system configuration and heat transfer section (black-box) (combined cycle—two pressure levels).

The proposed method aims at quantifying the optimal heat transfer interactions by means of an optimization of the design parameters of the overall system configuration. The temperatures at the boundaries of the black-box are considered as design parameters in addition to all the other design parameters related to the basic system configuration. The decision variables of the optimization process are to be chosen in this enlarged set of design parameters, a part of which is fixed by system technological characteristics or limits (e.g., the maximum temperature of a Rankine cycle is chosen according to the properties of the material for the boiler and turbine first stage), or by system control strategy and ambient conditions.

The outcome of the optimization procedure is the optimal set of overall system design parameters (including the values of the temperatures at the black-box boundaries) that guarantees the optimal matching between hot and cold thermal flows in the heat transfer section, according to the objective(s) that are set for the *overall system*.

5. Example of application

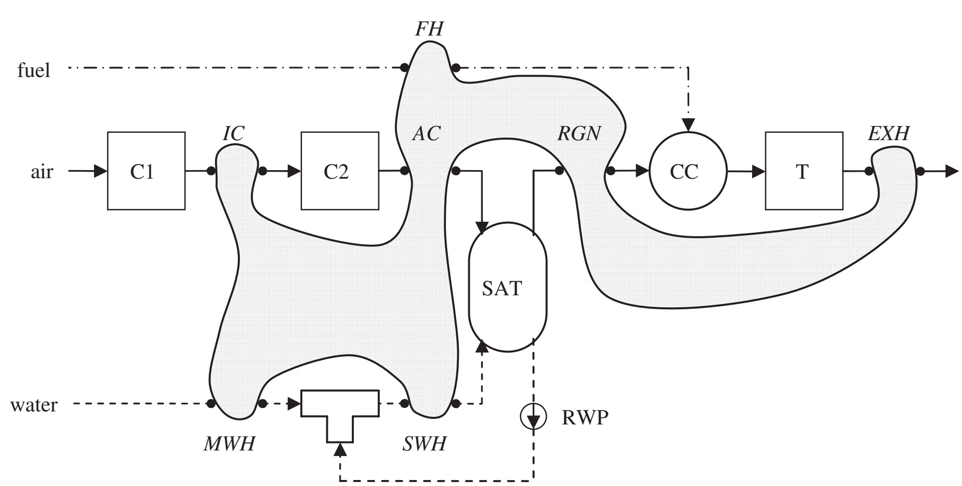
The method described above is applied in this section to a HAT plant [21]. The first step is the definition of the basic system configuration, i.e. the basic components outside the heat transfer section (black-box). The concept behind a humid air turbine is to increase the performance of a regenerative gas Brayton–Joule cycle by saturating the compressed air stream with water vapor. The key system component is therefore the saturator that is added to the traditional architecture of the regenerative Brayton cycle, which consists of a compressor, an air preheater, a combustion chamber and a turbine.

The heat transfer interactions in a HAT plant are quite complex, and this is the reason why it is a good test for a non-trivial optimization. The basic system configuration used in this work is shown in Fig. 6, where the components of the basic system configuration can be identified:

- A two stage (C1 and C2) compressor, which allows for an intercooling device between the two stages;
- The saturator (SAT), which is fed by a water stream that results from the mixing of make-up water and the water recuperated from the bottom of the saturator itself;
- The combustion chamber (CC);
- The turbine (T), which is directly fed by the combustion chamber.

Note that the sequence of processes associated with the cycle dictates the order of these components. Therefore they always appear and have a fixed position in the system structure, i.e. they completely define the basic system configuration. As it appears from Fig. 2, the plant configuration results from the composition of an air–gas cycle including C1, C2, SAT, CC and T, and a water–steam cycle including SAT, CC and T.

All the temperature links among these basic components are interrupted with the exception of the direct links between the hot source device (combustion chamber) and the turbine, and between the ambient and the first compression stage, according to the criterion explained in Section 3. In this sense the regenerator is not considered as



C1:	1st compression stage	*IC*:	intercooler
C2:	2nd compression stage	*AC*:	aftercooler
CC:	combustion cham ber	*MWH*:	make-up water heater
SAT:	saturator	*SWH*:	saturator water heater
T:	turbine	*RGN*:	regenerator
RWP:	recuperated water pu mp	*FH*:	fuel heater
		EXH:	exhaust gas cooler

Fig. 6. Basic system configuration and heat transfer section (black-box) of the HAT cycle used as example of application.

a "basic" component, since its presence in the system structure has to be verified by the optimization procedure.

In fact, according to the proposed methodology, the hot and cold thermal flows involved in the regeneration process corresponds to the temperature links that are cut between the true "basic" components: the link cut on the hot side, which generates the hot flow of exhaust gases, is between the turbine and the ambient, the two links cut on the cold side, which generate a cold flow of humid air and a cold flow of fuel, are between the saturator and the combustion chamber (humid air), and between the ambient and the combustion chamber (fuel). This representation allows to evaluate the optimal thermal energy recovery from the exhaust gases, and, theoretically, also the option of eliminating it.

The other links that are cut in the basic plant configuration (i.e. the other candidate hot/cold flows) are those between:

- The two compression stages (intercooling);
- The second compression stage and the saturator (after-cooling);
- Make-up water inlet and mixer;
- Mixer and saturator.

For sake of clarity, the links that are cut are named in Fig. 6 after the heat transfer devices in the real plant. According to this basic plant configuration, it is most likely that the hot and cold flows inside the black-box will be those in Fig. 7. In fact, the sign of temperature variations is not defined a priori, and the result of the optimization process may not confirm, in general, this classification.

A mathematical model of the basic plant configuration was developed in the Matlab–Simulink environment. In the model flowsheet the temperature links that are cut in the basic system configuration are represented by simple blocks that appear between the more complex blocks that represent the basic components. The former blocks are simple because they just pass some signals from the outlet of the preceding component to the inlet of the subsequent one: the signals associated with mass flow rate, pressure and chemical composition are unaltered, whereas a variation is added to the signal associated with temperature.

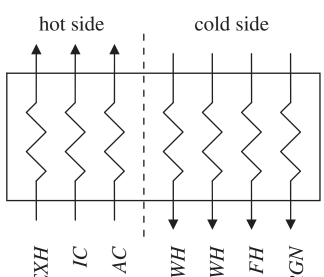


Fig. 7. Hot and cold flows (expected) in the black-box.

According to the links that are cut in the basic plant configuration the following temperatures are free to vary at black-box boundaries:

- The second compression stage inlet temperature ($T_{C2,in}$, at IC outlet), whereas the first compression stage outlet temperature ($T_{C1,out}$, at IC inlet) is fixed by the inlet conditions, the pressure ratio and the isentropic efficiency of the first compression stage;
- The saturator air inlet temperature ($T_{sat,in}$, at AC outlet), whereas the second compression stage outlet temperature ($T_{C2,out}$, at AC inlet) is fixed by the inlet conditions, the pressure ratio and the isentropic efficiency of the second compression stage;
- The saturator air outlet temperature ($T_{sat,out}$, at RGN inlet);
- The saturator water inlet temperature ($T_{satw,in}$, SWH output), whereas the recuperated water pump fixes the temperature (T_{mix}) at which make-up water and recuperated water are mixed (MWH output and SWH input);
- The recuperated water temperature at saturator outlet (T_{rw}) (thus the mass flow rate of water vapor is evaluated from the enthalpy balance of the saturator);
- The combustion chamber (humid) air inlet temperature ($T_{cc,in}$, at RGN outlet);
- The combustion chamber fuel inlet temperature ($T_{cc,fuel}$, FH outlet).

Some of the variables included in the overall set of independent variables of the model are fixed as parameters. The turbine inlet temperature (1250 °C) and the compressor pressure ratio (20) are fixed according to the desired plant technological level. The inlet air mass flow rate of the plant is fixed at 100 kg/s, the ambient conditions are 1.013 bar, 15 °C and 60% relative humidity. Water conditions at make-up water inlet are 45 bar and 15 °C. Fuel inlet conditions are 40 bar and 15 °C. The temperature of the exhaust gases is fixed at 105 °C to allow heat recovery to proceed until condensation of corrosive chemical species occurs. Component performance parameters are also fixed: isentropic efficiencies of the compression stages (0.88 for both), turbine (0.9) and pump (0.8), the pressure losses in the saturator (0.7%) and in the combustor (3%).

The decision variables of the model are:

- The pressure ratio of the first compression stage (r_{C1}, which determines $T_{C1,out}$);
- The second compression stage inlet temperature ($T_{C2,in}$);
- The saturator air inlet temperature ($T_{sat,in}$);
- The temperature variation of the air stream in the saturator ($\Delta T_{sat} = T_{sat,out} - T_{sat,in}$);
- The temperature variation across the regenerator ($\Delta T_{rgn} = T_{cc,in} - T_{sat,out}$);
- The temperature difference between saturator air inlet and water outlet temperatures ($\Delta T_{w,in} = T_{sat,in} - T_{rw}$);

- The temperature difference between saturator air outlet and water inlet temperatures ($\Delta T_{\rm w,out} = T_{\rm satw,in} - T_{\rm sat,out}$);
- The combustion chamber fuel inlet temperature ($T_{\rm cc,fuel}$).

The optimization procedure is carried out using the sequential quadratic programming algorithm of MATLAB Optimization Toolbox for non-linear constrained optimization. The constraints are the limits chosen for the ranges of the decision variables and the feasibility of the heat transfer. The latter is verified by constructing the ‘‘problem table’’, according to the procedure in [6]. This starts with both the high temperature extremes of the composite curves at the abscissa $Q = 0$, since in this case no additional external hot sources are available. At any temperature interval the problem table assesses the cumulative surplus of heat available for the cold thermal flows from the hot ones. The constraint on heat transfer feasibility is expressed by an inequality according to which the minimum heat surplus must not fall below zero for the assigned minimum temperature difference (10 °C in this example). This formulation of the heat transfer feasibility constraint is more useful to the optimization algorithm than the definition of a boolean flag indicating whether or not the composite curves intersect.

The results of the optimization (Table 1 and Fig. 8) are the optimal values of the temperatures selected as decision variables. These temperatures define the hot and cold thermal flows made available and required, respectively,

Table 1
Optimal temperature values at black-box boundaries

	IC	AC	EXH	MWH	SWH	FH	RGN
$T_{\rm in}$	208.2	183.1	577.2	15	65.9	15	132
$T_{\rm out}$	25	85.6	105	65.9	176.2	566.8	566.3

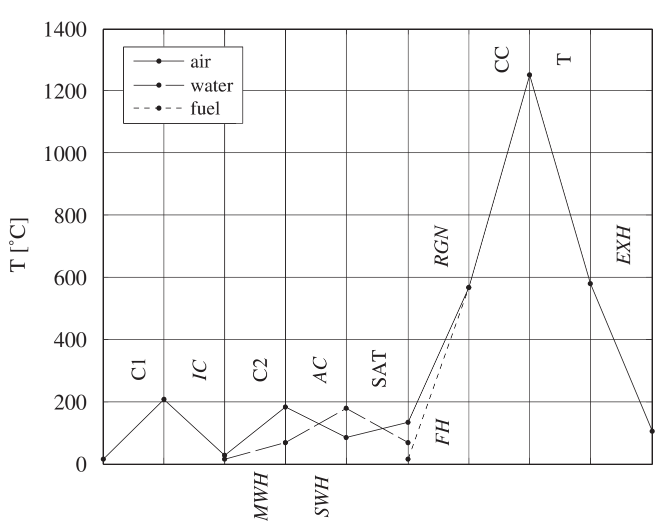


Fig. 8. Temperature profiles for maximum system exergetic efficiency.

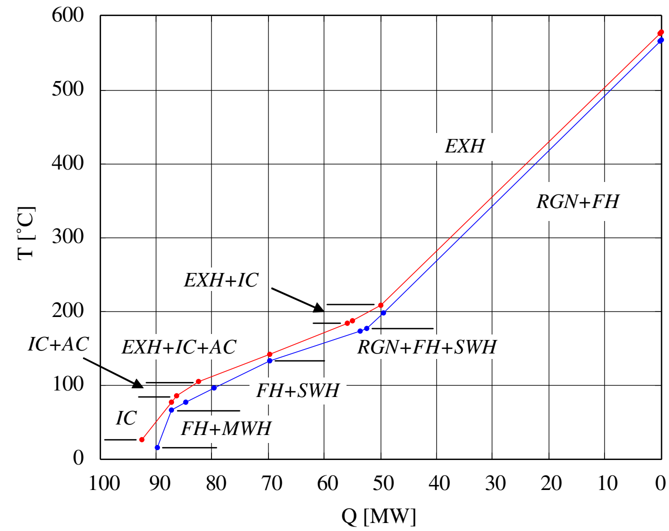


Fig. 9. Optimal composite curves for maximum system exergetic efficiency.

within the system. These are conveniently represented by the composite curves in Fig. 9. The curves are almost parallel at any temperature level, and this demonstrates that the original choice of the basic plant components in the HAT cycle allows the hot flows available to be exploited in an almost ‘‘ideal’’ way. In fact, the cold flows made available by this choice can be matched with the hot ones in such a way that the temperature difference is kept to the minimum possible value (10 °C) at nearly all temperature levels. In particular, this appears in the upper temperature range (the right part of the curves), because the heat capacities of the exhaust gases (EXH), on the hot side, and the humid air (RGN) and fuel flows (FH), on the cold side, result to be very similar. Moving to the left (lower temperatures), the hot thermal flows of intercooled air (IC), aftercooled air (AC) and exhaust gases (EXH) are matched with the cold flows of humid air (RGN), make-up water (MWH), saturator feed water (SWH) and fuel (FH). In the temperature range between 200 and 70 °C, the heat capacities of the hot and cold thermal flows involved (see Fig. 9) are still quite similar, and three points appear where the temperature difference between the composite curves approaches the minimum value (10 °C) (at about 200, 140 and 70 °C).

In the left-most part of the curves, a proper matching between the hot and cold flows heat capacities cannot be achieved. In fact, the water mass flow rate (9.68 kg/s) required to saturate the compressed air stream is one order of magnitude lower than the compressed air mass flow rate itself (100 kg/s), whereas the constant pressure specific heat is only four times as much. On the other hand, the objective of the optimization procedure is to improve the exergetic efficiency of the total plant and does not necessarily coincide with the search for an ideal heat recovery within the heat transfer section, i.e. the decision variable values that would maximizes heat recovery may adversely affect the contribution to overall efficiency that results from the thermodynamic parameters of the basic plant components.

6. Conclusions

The synthesis of system components is a complex problem involving several inter-dependent aspects: one of these is the exchange of thermal energy resources within system boundaries.

The paper shows how the synthesis of the components belonging to the heat transfer section can be separated from the synthesis of the other ''basic'' components, which instead define the main system characteristics. So, *the variables associated with the position and number of heat exchangers can be excluded from the set of free variables in the general problem of the synthesis of system components*.

Once the sequence of basic components is defined, the ''thermal'' links among them are cut to allow heat flows to be released or required, showing up the decision variables associated with internal heat transfer. The thermodynamic variables associated with the basic components complete the set of decision variables. The thermodynamic optimization of this new ''basic'' configuration of the system, perfectly coincident with the complete one from the mathematical point of view, generates optimal values of all the decision variables involved, and in particular, of those at the heat transfer section boundaries.

The optimization procedure applied to a HAT cycle plant showed that the optimal exergetic efficiency for the overall system corresponds to ''almost perfect'' heat transfer conditions between the various hot and cold thermal flows within the system boundaries (i.e. the minimum temperature difference between hot and cold composite curves is achieved at almost any temperature level). This demonstrates that the procedure is effective in exploiting all the internal heat sources of the HAT cycle. So, the power gain in the expansion process due to the increase in turbine mass flow rate is obtained with a reduction in compression power, and a consequent increase in the efficiency.

The procedure can be applied to any kind of plant including one or more thermodynamic cycles, and it is intended to be a part of a wider approach dealing with the definition of the basic system configuration, as discussed in the paper.

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