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A Virtual-system Concept for Exergy Analysis of Flow Network Plant; Part I: Principles

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ABSTRACT

A new type of virtual system, named a flow constraint system (FCS), is proposed to facilitate, clarify, and simplify exergy analyses of plant that involve material flow networks. The need for the virtual system is outlined and the concept is demonstrated by applying it to a CHP steam cycle. The FCS concept allows the physical constraints on the exergy interactions associated with flow streams to be taken into account fully. It also simplifies the treatment of bifurcations in material flows and considerably reduces the need for absolute exergy evaluations. The new concept follows from the work already published by the authors on conceptual devices for exergy analysis and builds on this and the work of other authors relating to exergy and exergoeconomic analysis, especially using matrix methods. A bond graph type of diagram is described as an alternative to the usual Grassmann diagram. A numerical illustration is given in a separate paper — Part II.

NOMENCLATURE

Abbreviations
CHP Combined heating and power
FCS Flow constraint system
LFCS   Linked flow constraint system
RN   Reversible node

Symbols
b Specific flow exergy function $(b = h - T_o s)$

h Specific enthalpy

s Specific entropy

T_o Temperature of the environment

$\dot{E}_{13}$ Exergy interaction rate with subscript identifier

$\dot{E}_{(4-5-6)}$ Exergy interaction rate that is the algebraic sum of the exergy interactions identified by the signed subscripts $(\dot{E}_{(4-5-6)} = \dot{E}_4 - \dot{E}_5 - \dot{E}_6)$

INTRODUCTION

In this paper a new, simple, and powerful concept is presented to deal with real constraints, which have generally been neglected, on the net exergy interactions due to the transport of exergy by material flows between subsystems and external systems of plant.

A DISCUSSION OF CONVENTIONAL SYSTEMS, AS BACKGROUND

A system can be conventionally defined as a region in space surrounded by a boundary, which can be either real or imaginary. It is closed if no transfer of matter occurs across the boundary; and otherwise it is open.

Beretta and Gyftopoulos (1990) have given a very general definition of the state of a system: a vast amount of data may be required to describe it. However, if a system is in equilibrium its state can be described by means of a relatively small number of parameters. An example would be a simple closed system that contains a gas in equilibrium: it could be described by specifying the gas and stating two independent properties such as pressure and specific volume: the state would be the same throughout the system; i.e., all subsystems would have the same state.

It is also possible that the state might vary throughout a system
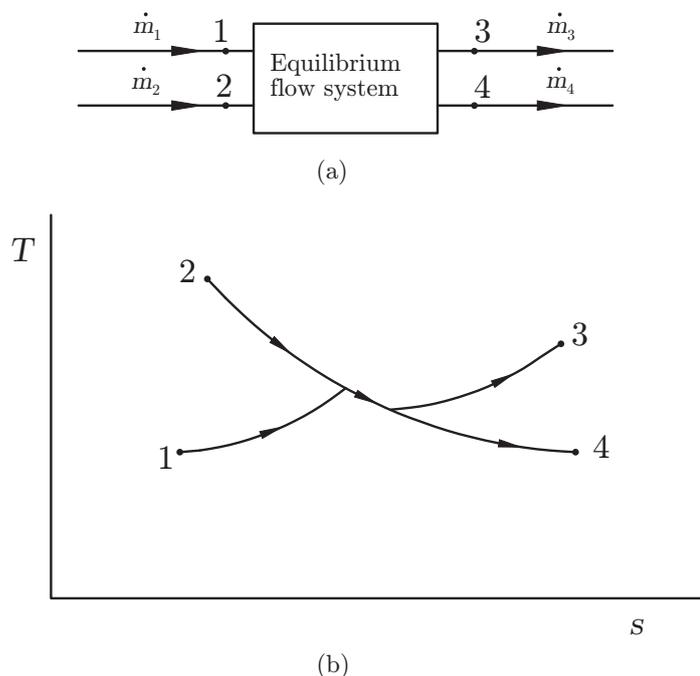

Fig. 1 (a) An equilibrium (reversible) flow system with two entry and two exit streams, all of the same fluid.
(b) The reversible process paths for the equilibrium flow system in (a) shown on a T-s diagram.

that is conceived to be in equilibrium: a flow system that involves an equilibrium process of a substance, which enters at a particular thermodynamic equilibrium state and leaves at a different one, is an example. Such an equilibrium system can be regarded as being composed of an infinite number of infinitesimal subsystems at different equilibrium states — these states form a continuous path from the inlet to the outlet state. An equilibrium flow system can be described by specifying the equilibrium path and quantifying the distribution and composition of matter over the path. There may also be multiple inlet and outlet flows and multiple paths that combine or separate, as represented in Fig. 1.

An entire plant may consist of interlinked devices through which streams of matter pass. These streams combine or separate at various positions within the plant and so comprise a flow network. Sometimes an entire plant can be regarded as a closed system made up of various open flow systems; for example, the sealed refrigerant circuit of a domestic refrigerator is made up of open systems such as the compressor and the condenser linked together. Sometimes again, matter passes through the boundary of an entire plant, which must be regarded as an open system; a gas turbine engine with internal combustion would be an example.

For analysis purposes it may be possible to model some of the flow systems within a plant as equilibrium systems (e.g., a length of pipe in which the pressure drop and heat loss are negligible), but for detailed analysis this would be the exception rather than the rule. However, it is usually possible to identify flow positions at the boundaries of plant components where the equilibrium state, the specific potential and kinetic energies, and the composition of the flowing substance can be identified — this involves some approximation, as the flow parameters are likely to vary somewhat over the cross section at a given position.

Overall exergy and energy analyses normally include sub-analyses of the linked flow systems that comprise the plant; under the assumption that equilibrium conditions exist at the positions of linkage. At these positions, energy and exergy are transported from one subsystem to another. Besides the interactions between subsystems due to transport (i.e., with material that crosses a boundary), there may be other interactions due to transfer: energy is transferred as work or heat; and exergy is transferred as work or in association with heat (the exergy transfer associated with heat may differ in magnitude and/or direction from the heat transfer).

EXERGY TRANSPORT CONSTRAINTS

The usual approach in energy and exergy analysis has been to treat transport interactions in the same way as transfer interactions (Grassmann, 1950; Szargut, 1956; Riekert, 1974). For example, the exergy transport rate due to flow at a boundary is the product of the specific flow exergy (often including the chemical exergy) and the mass flow rate; this would be combined with any exergy transfers into the system due to work or heat. A disadvantage of this is that the inherent constraints on the net exergy interaction due to exergy

transport are not taken into account; for example, if steam enters and leaves a turbine at known states with negligible values of specific kinetic and potential energy, and the temperature of the environment is also known, the net exergy interaction due to transport is fully defined — it equals the difference between the flow exergy function ($h - T_o s$) at inlet and that at the outlet. This net exergy interaction is independent of the pressure and the composition of the environment (Sussman, 1980). The true input to the turbine is the net exergy interaction due to transport: this has the characteristic (like exergy transfer due to heat) of being dependent on no property of the environment other than temperature.

O'Toole and McGovern (1990) have shown by means of conceptual devices how the net exergy transport due to flow streams (including the case of fuel and air that react to give combustion products) that enter and leave a system is fully equivalent to an exergy transfer. This approach can lead to simplification and clarification of exergy analysis. For example, a heat exchanger that transfers heat from one flowing fluid to another is viewed as a device with one net exergy input and one net exergy output interaction. A throttle valve in a steam or refrigeration circuit is seen as a device with a net exergy input and no net exergy output: it has a rational efficiency of zero, as the net exergy input is totally destroyed.

However, a new type of difficulty arises, which is illustrated by the following example. A turbine has an input stream coming from a boiler and an output stream to a condenser, Fig. 2. If the net exergy input to the turbine is the difference between the input and output
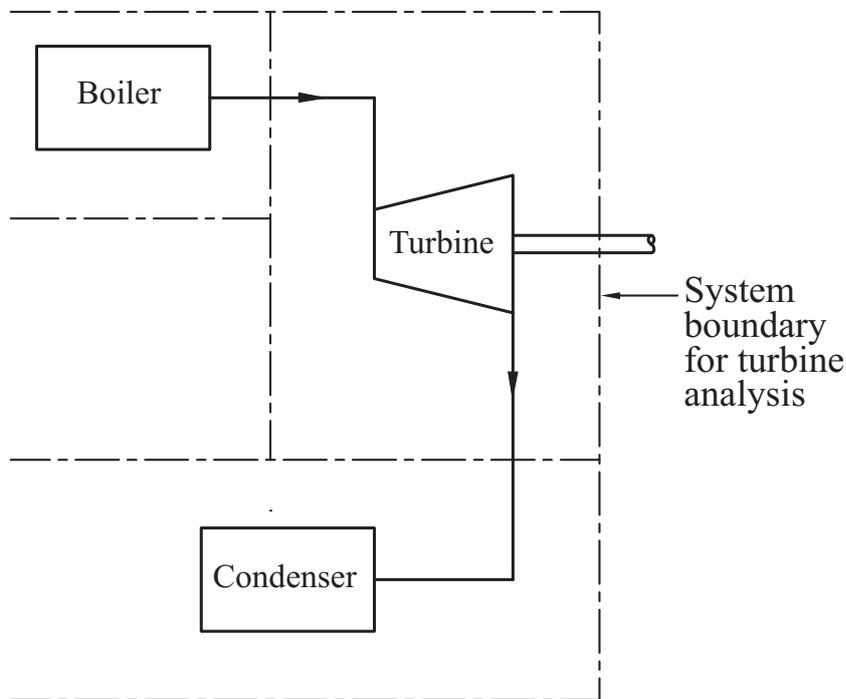

Fig. 2 Illustration of an analysis boundary for a turbine: partial boundaries for two contiguous systems that provide or receive material flow are also shown.

flow exergy functions, from which system does the net exergy interaction occur? A valid answer would be that the source of the net exergy input is the remainder of the plant, which includes both the boiler and the condenser. However, pursuing this approach without modification would complicate the analysis methodology since each plant component within a flow network would interact with a different system (the remainder of the plant excluding that component).

THE FLOW CONSTRAINT SYSTEM

A new flow constraint system (FCS) is proposed to resolve the difficulties that have been mentioned and as the basis for a totally new methodology for applying exergy techniques (and also energy techniques) to flow network plant. An FCS is a virtual system defined as a set of disjointed infinitesimal flow systems at the positions where flow streams cross an analysis boundary, such that the substances that pass through elements of the set belong to the same impermeably-bounded space within the system. For the turbine mentioned above, the FCS would consist of an infinitesimal flow system through which the full flow of steam passes at the inlet state and another infinitesimal flow system through which the full flow of steam passes at the outlet state, Fig. 3. The FCS is fully described by quantifying the composition, flow rate, flow direction, thermodynamic state, and specific kinetic and potential energy at each flow position on the boundary. The FCS includes no irreversibility or exergy destruction since the flow systems that comprise it are infinitesimal. The FCS incorporates the constraints on the exergy transport interactions to or from a plant component with a specified analysis boundary.
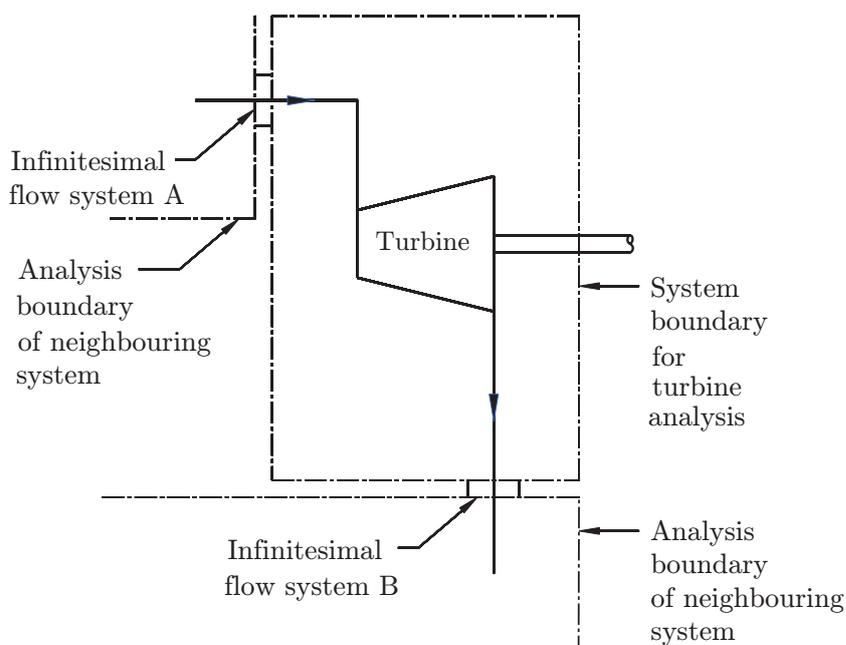

Fig. 3 The same plant component as in the previous figure with two infinitesimal flow systems added. The FCS of the turbine consists of the two infinitesimal flow systems at A and B.

A discrete plant component may have a characteristic FCS, or several characteristic FCSs; for example, a heat exchanger usually has two FCSs, corresponding to two independent streams of fluid that pass through it (each stream occupies a different impermeably-bounded space within the system).

STRUCTURAL TRANSPORT CONSTRAINTS — THE LINKED FLOW CONSTRAINT SYSTEM

There are also structural constraints on the net exergy transport interactions, which have to do with the way the components are connected together; for example, in a refrigerator the compressor, condenser, expansion device, and evaporator are connected in series. The net exergy interactions of the components due to transport of fluid are not independent: any change in a net exergy interaction of one component with its FCS will affect a net exergy interaction of at least one of the other components with its FCS. The term "linked flow constraint system" (LFCS) will be used for a virtual system that is the union of more than one FCS and where all constituent FCSs are linked so as to belong to the same continuous, impermeably-bounded space. Just as a constraint on a net exergy interaction of a component is taken into account by an FCS of that component, so an LFCS takes account of structural transport constraints. An LFCS of a refrigerator could consist of four infinitesimal flow systems; one at entry to each of the four components (compressor, condenser,
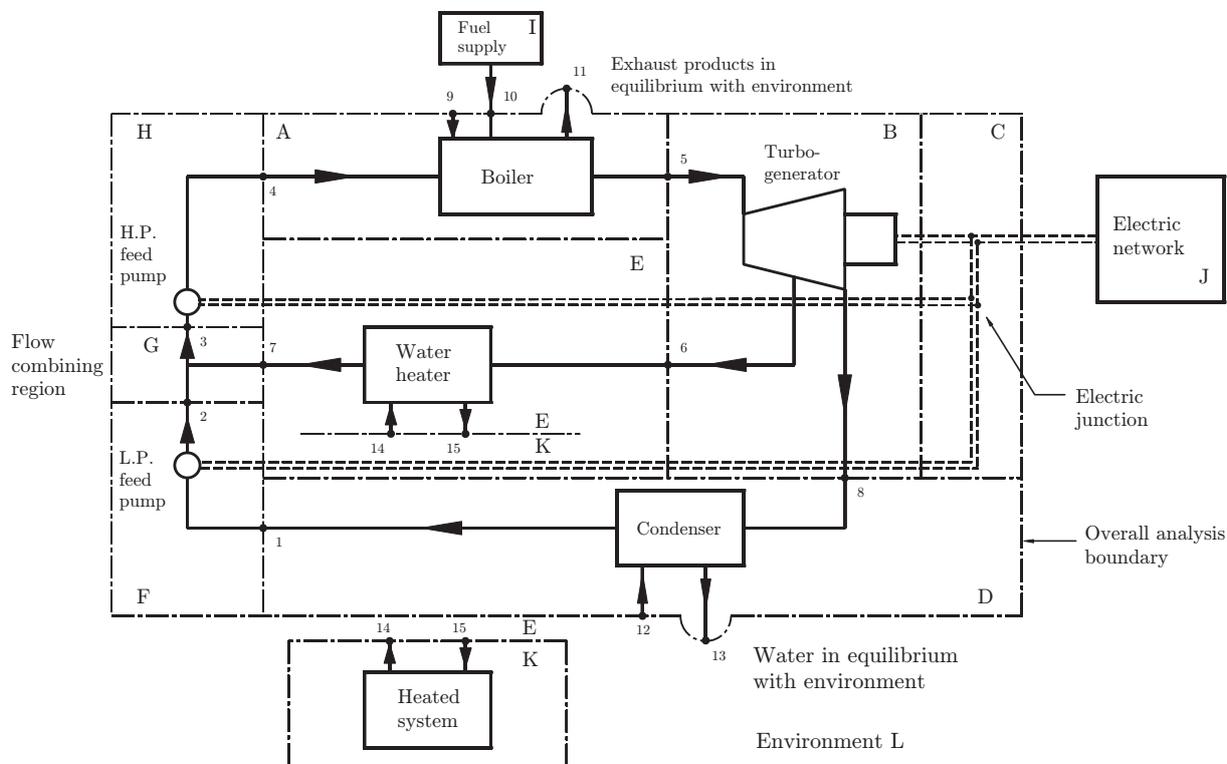

Fig. 4 Schematic representation of a CHP steam plant: this incorporates the analysis boundary definitions.

expansion device, and evaporator) connected in series. A more detailed example is presented in the next section.

A COMBINED HEATING AND POWER STEAM PLANT

Fig. 4 is a schematic diagram of a CHP steam plant that provides power and useful heating. The overall analysis boundary of the plant and the subsystem boundaries for analysis of components are shown. It should be noted that there are restrictions on the representation of three-dimensional space on a two-dimensional diagram. For example: subsystem E (which is inside the overall analysis boundary) and subsystem K (which is outside the overall analysis boundary) are contiguous. The water pipes on which points 14 and 15 are located do not pass through subsystem D. The electric cables could pass through various subsystems, but, as they involve negligible exergy destruction, they would have only negligible net exergy interactions with any of the systems they might pass through.

Choice of Boundaries

The environment, system L, is defined to consist of saturated air and liquid water, in equilibrium at a specified temperature and pressure. The bulges shown on the overall analysis boundary at positions 11 and 13 represent the fact that the boundary is drawn sufficiently far from the discharge stream outlets that matter crosses the boundary only after it has reached full equilibrium with the environment. The effect of specifying the boundary in this way is to include all irreversibilities within the overall analysis boundary — an alternative approach would be to define additional external systems that would receive the discharge streams at specified states; or to further divide sub regions A and D in order to identify the exergy destruction due to mixing with the environment in each case. Freedom to choose the boundary is not compromised.

External Systems

The only exergy source is the fuel supply, which provides a flow of fuel at a specified state. There are two exergy sinks: the electric network J, which receives electric power; and the heated system K, which receives a flow of heated water at state 15 and provides the same mass flow rate of water at a lower temperature at state 14.

Subsystems and Interactions

The plant within the overall analysis boundary has been partitioned into eight subsystems: A to H. There are material flow (transport) and electric power (transfer) interactions that involve these subsystems and the external systems. Heat transfer to the environment also takes place from some of the subsystems, but, as this occurs at the temperature of the environment, there are no associated exergy interactions.

The FCSs of subsystems A, B, D, E, F, G, and H for the water/steam working fluid can be linked to give an LFCS consisting of infinitesimal flow systems at points 1 to 8 — this will be called LFCS1. The boiler subsystem also has an FCS for the air, fuel, and
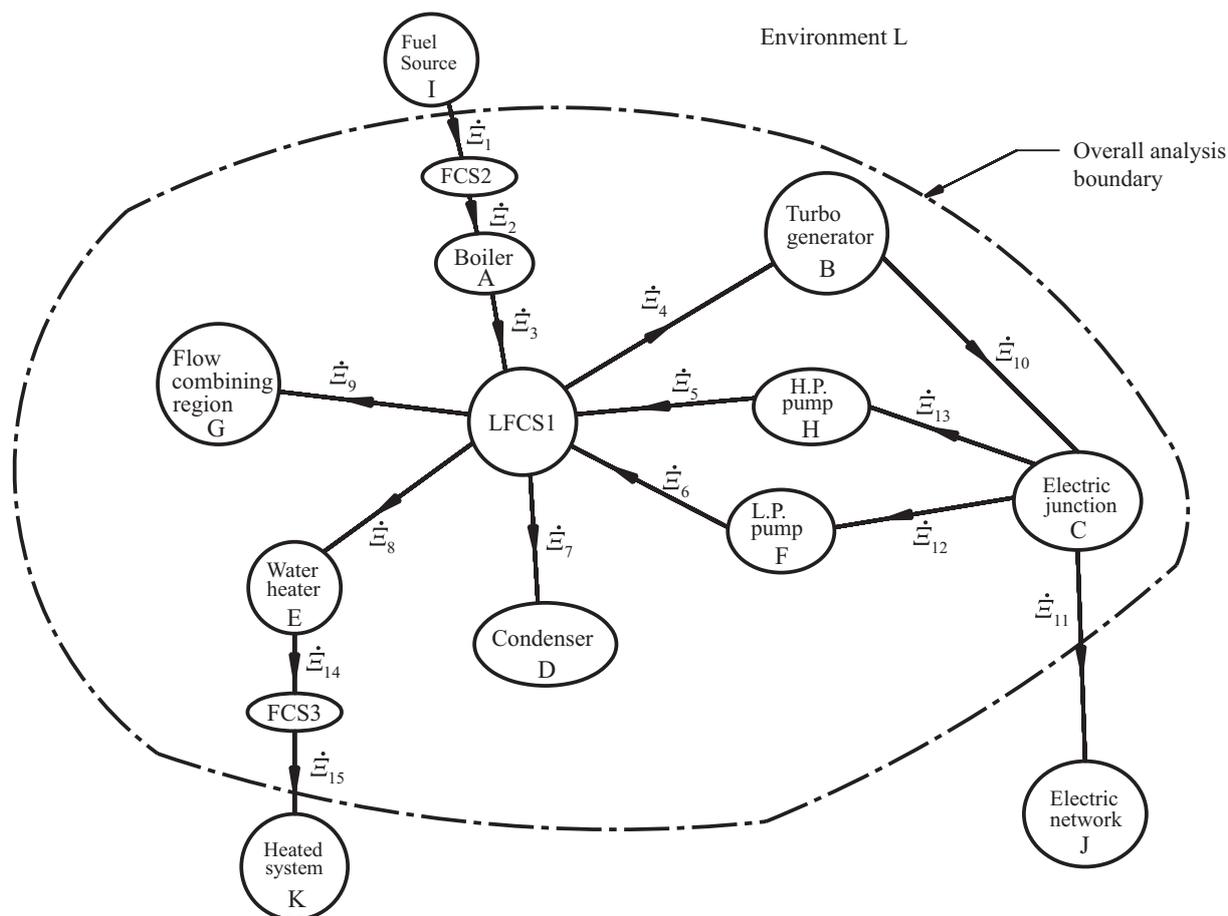
Fig. 5 Exergy interaction diagram, based on the flow constraint system
concept, for the CHP steam plant shown in Fig. 4.

combustion products; involving points 9, 10, and 11 — FCS2. The
condenser subsystem could have an FCS for the cooling water stream
involving points 12 and 13, but this would not feature in the analysis
since it involves a net exergy interaction of zero (the flow exergy at
point 12 and that at point 13 are both zero). The water heater and the
heated system have a common FCS involving points 14 and 15 —
FCS3. It will be seen that FCS2 and FCS3 are trivial and could be
omitted. LFCS1, however, provides a link between many of the plant
subsystems that takes into account the constraints on exergy transport
interactions. Fig. 5 is the net exergy interaction diagram for the plant
— it is a new type of diagram for the application of exergy
techniques and has the form of a bond graph.

The net exergy interactions between the systems and subsystems
in Fig. 5 can be evaluated by conventional means. There is a useful
simplification compared to conventional approaches in that the net
exergy interactions of an FCS or LFCS can be evaluated without
reference to the pressure or composition of the environment; for
example, in evaluating all exergy interactions of LFCS1 in Fig. 5 the
flow exergy function $b = h - T_o s$ can be used, with values of h and
s taken from standard steam tables.

Material Flow Bifurcation

Subsystem B in Fig. 4 contains a material flow bifurcation. In typical exergetic or exergoeconomic analysis approaches, this would also give rise to exergy flow and cost bifurcations, the relative values of which would depend on the pressure and composition of the environment or on a subjective specification of the zero state for the flow exergy function. As illustrated in Fig. 5, this situation does not give rise to a net exergy interaction bifurcation when the FCS concept is applied.

Rational Efficiencies

The rational efficiency of the plant (as defined by the overall analysis boundary shown in Fig. 4 and Fig. 5) is the sum of the exergy output rates $(\dot{\Xi}_{11} + \dot{\Xi}_{15})$ divided by the exergy input rate $\dot{\Xi}_1$. Also, the rational efficiency of any subsystem is the sum of its exergy output rates divided by the sum of its exergy input rates. The virtual systems LFCS1, FCS2, and FCS3 are reversible and have rational efficiencies of unity.

Having defined all systems, and subsystems having being defined by their analysis boundaries, there is no ambiguity or subjectiveness whatsoever about the definition of the plant or subsystem rational efficiencies. The flow constraint system concept inherently incorporates a recommendation by Tsatsaronis and Winhold (1985) to use when possible differences of exergy flow streams in the definition of exergetic efficiencies.

It can be noted that the condenser has a rational efficiency of zero; based on its analysis boundary, which includes the region where the warm discharge water mixes irreversibly with the local surroundings before exiting in equilibrium with the environment. An alternative approach would be to define an additional boundary to separate the heat exchanger from the mixing region. In this case a finite rational efficiency would be obtained for the condenser that would describe its performance as a heat exchanger between flow streams; the rational efficiency of the mixing region would be zero.

Exergy Destruction Sinks

In Fig. 5 there are two exergy destruction sinks within the overall analysis boundary: these are the condenser D and the flow combining region G (as defined in Fig. 4). Exergy destruction sinks are undesirable aspects of a plant's structure: the design objective should be either to eliminate them, or to minimise the net exergy interactions to them.

Exergy Recycles

There are two exergy recycles in Fig. 5, involving systems LFCS1, B, H, F, and C. From the exergy interactions shown the performance of the turbogenerator and each of the two pumps as discrete components can be quantified by calculating their individual rational efficiencies. However, it is thermodynamically undesirable to recycle exergy through devices that have rational efficiencies less than unity. (Indeed, it is a particular strength of the steam cycle that

the amount of the eventual exergy as electric power that is recycled through the feed pumps is small.) Exergy recycles are structural weaknesses that have implications for the exergetic and economic costs of the final products. The exergy interactions that constitute a recycle are not independent, but are structurally constrained in a way that causes exergy destruction.

A new type of transformation of interactions between subsystems is proposed to clarify the nature of recycles and replace them, for analysis purposes, by equivalent direct interactions. This is somewhat analogous to a delta-star transformation in electrical network theory. Fig. 6 incorporates the transformed exergy interactions that replace the recycles of Fig. 5. The arrows are drawn so that all exergy interactions are positive. The five transformed exergy interactions are related to the original six exergy interactions by the following equations, which replace the recycle interactions by single exergy interactions with each of the systems involved:
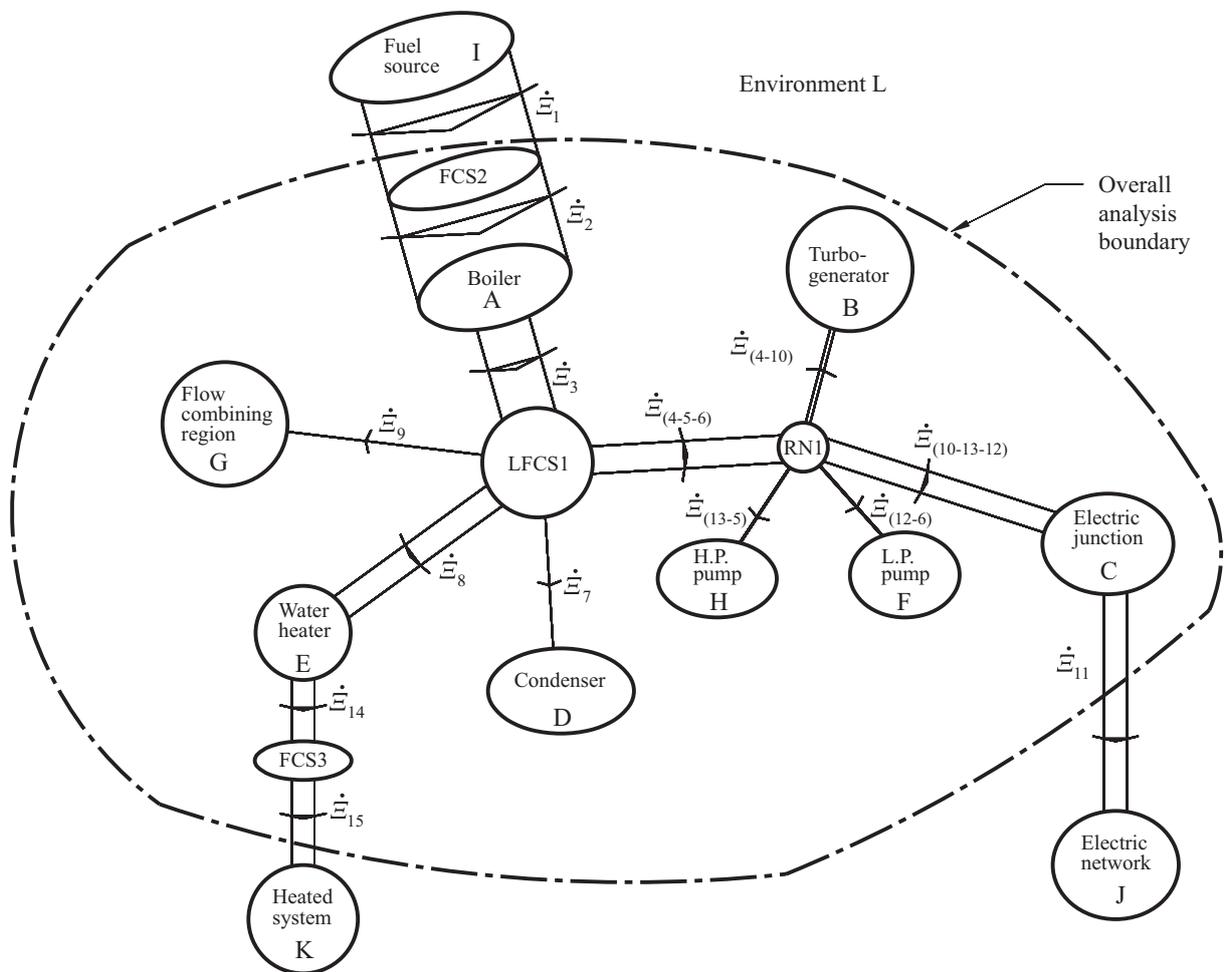

Fig. 6 Alternative exergy interaction diagram to that shown in Fig. 5; incorporating transformed interactions and a reversible node that have eliminated two recycles.

$$\dot{\Xi}_{(4-5-6)} = \dot{\Xi}_4 - \dot{\Xi}_5 - \dot{\Xi}_6 \qquad\qquad \dot{\Xi}_{(4-10)} = \dot{\Xi}_4 - \dot{\Xi}_{10}$$

$$\dot{\Xi}_{(10-13-12)} = \dot{\Xi}_{10} - \dot{\Xi}_{13} - \dot{\Xi}_{12} \qquad\qquad \dot{\Xi}_{(12-6)} = \dot{\Xi}_{12} - \dot{\Xi}_6$$

$$\dot{\Xi}_{(13-5)} = \dot{\Xi}_{13} - \dot{\Xi}_5$$

This transformation introduces a reversible node, labelled RN1 in Fig. 6: it is reversible because the sum of the exergy outputs equals the sum of the exergy inputs; that is,

$$\dot{\Xi}_{(4-10)} + \dot{\Xi}_{(10-13-12)} + \dot{\Xi}_{(12-6)} + \dot{\Xi}_{(13-5)} = \dot{\Xi}_{(4-5-6)}.$$

When viewed in the context of the new set of systems (i.e., the previous ones plus RN1) the turbogenerator and the two feed pumps are seen as exergy destruction sinks (Fig. 6). The rational efficiencies of the turbogenerator and pumps as discrete components do influence the overall plant rational efficiency, but not in a multiplicative chain-rule way — an exergy destruction sink can be produced by linking even highly efficient discrete components in a recycle.

In Fig. 6 band widths proportional to the exergy interactions are used. In this way the new exergy diagram can retain one of the most valuable attributes of Sankey and Grassmann diagrams: the representation to scale of interaction magnitudes.

CONCLUSIONS

A totally new concept, the flow constraint system, has been described for use in exergy analysis of flow network plant (it can also be applied in energy analysis). This allows the constraints on the net exergy transport interactions of discrete components to be taken into account fully. Structural transport constraints due to the way components that involve material flow are linked together are also taken into account. In comparison with conventional approaches, analysis procedures are simplified since multiple exergy flow streams are replaced by net exergy interactions and the need for absolute exergy evaluations is greatly reduced. Plant and subsystem rational efficiencies are defined in an objective way. A technique for the transformation of an exergy interaction network to eliminate recycles has been presented. A new bond-graph-type exergy interaction diagram has been described. The virtual system that is a set of disjointed, infinitesimal systems is simple: the authors have found it to have great power to clarify the structure of plant in exergy terms. It is ideally suited for use with matrix methods of exergy and exergoeconomic analysis (Valero et al., 1986): this is illustrated in Part II.

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