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A systematic approach to plant-wide control based on thermodynamics

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Abstract

In this work, a systematic approach to plant-wide control design is proposed. The method combines ingredients from process networks, thermodynamics and systems theory to derive robust decentralized controllers that will ensure complete plant stability. As a first step, the considered process system is decomposed into abstract mass and energy inventory networks. In this framework, conceptual inventory control loops are then designed for the mass and energy layers to guarantee that the states of the plant, both in terms of extensive and intensive properties, will converge to a compact convex region defined by constant inventories. This result by itself does not ensure the convergence of intensive variables to a desired operation point as complex dynamic phenomena such as multiplicities may appear in the invariant set. In order to avoid these phenomena, thermodynamics naturally provides the designer, in these convex regions, with a legitimate storage or Lyapunov function candidate, the entropy, that can be employed to ensure global stability. Based on this, the control structure design procedure is completed with the realization of the conceptual inventory and intensive variable control loops over the available degrees of freedom in the system. To that purpose, both PI and feedback linearization control are employed. The different aspects of the proposed methodology will be illustrated on a non-isothermal chemical reaction network.

Keywords: Plant-wide control; Process networks; Irreversible thermodynamics; Inventory control

1. Introduction

Over the years, the area of plant-wide control has attracted the process engineering community as a challenging problem which drives continuing research efforts. By re-phrasing Professor S. Skogestad words (Larsson & Skogestad, 2000): *The objective of plant-wide control is not the tuning of a given set of control loops on a chemical plant but rather the control philosophy of the overall plant with emphasis on the structural decisions*. A number of solutions to it were suggested, lying in between the following two extremes:

(1) A *hierarchical decomposition* of the original control design problem based on heuristic rules. The heuristic logic is developed so to keep process variability and therefore the operational plant objectives under acceptable limits for a given set of disturbances (see Buckley, 1964; Luyben, Tyreus, & Luyben, 1997or Skogestad, 2002, for further information about this decomposition)
(2) A *mathematically oriented approach* based on the solution of a given large scale mixed integer nonlinear programming dynamic optimization problem, which in the limit should be able to simultaneously determine the optimal process units size and their interconnections as well as the optimal control scheme configuration (see Biegler & Grossman, 2004, for an excellent review).

Unfortunately, both lines of attack are hampered by a number of drawbacks which prevent their systematic application to general classes of process plants: on the one hand, the hierarchical approach usually leads to conflicting decisions only unravelled on a case by case basis. On the other hand, the mathematically oriented approach is limited by the high dimensionality of the problem, the nonlinear character of the constitutive equations and the restrictions imposed by the definition of the objective function. In addition, the stability and robustness of the resulting control scheme is highly dependent on the number, type and

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characteristics of plant disturbances. In fact, such disturbances usually need to be known beforehand as part of the control design problem. Furthermore, nothing prevents the resulting control configuration from exhibiting instabilities under a different class of disturbances.

To overcome these issues, we combine previous results that link thermodynamics with passivity and Lyapunov theory. The basic ingredients of the theory have been established by Alonso and Ydstie (1996) and Ydstie and Alonso (1997) in the context of passive control design and control of distributed systems (Alonso & Ydstie, 2001), and transport reaction systems (Ruszkowski, Garcia-Osorio, & Ydstie, 2005). A similar line of arguments was employed by Farschman, Viswanath, and Ydstie (1998) to derive mass and energy inventory control concepts. Hangos, Alonso, Perkins, and Ydstie (1999) applied them to define structural stability conditions for separation process networks. Thermodynamics was also central in the work by Bao, Zhang, and Lee (2002) to design passivity-based decentralized control of failure-tolerant systems.

In this paper, our aim is to apply and extend these results in order to systematically design stable decentralized control structures for process plants. The proposed approach leads to a hierarchical decentralized inventory control structure which simultaneously ensures convergence of mass and energy inventories to a compact convex set in which the system will remain on.

It must be pointed out that this convex region definition tries to generalize the approach by Hangos et al. (1999), where extensive variables are assumed constant, to derive the structural stability conditions. Once in this region, convergence of the intensive variables (temperatures, pressures and concentrations) to a unique stable steady-state can be enforced by a number of well established control schemes (for instance, PI control, feedback linearization controllers, etc.).

Finally, it must be remarked that our approach complements others such as the one recently proposed in the context of chemical reactors (Gonzalez & Alvarez, 2005) since it provides the designer with the required physical insight and systematic tools to select inputs and outputs, decide what variables to estimate, and select stabilizing control alternatives.

The present paper is structured as follows: in Section 2, a formal representation of chemical plants in terms of interconnected mass and energy networks is presented as a first step in designing control structures. In this section, we formally introduce the so-called inventory network and describe the general algebraic structure underlying its dynamics. The thermodynamic formalism and its application in designing conceptual inventory controllers are presented in Section 3. The realization of these control loops over the real available degrees of freedom of the process and the intensive control problem, as the final steps in the control design, are also developed in this section. Finally, in Section 4 the approach is applied to design a decentralized control structure for a non-isothermal reactor network.

2. The underlying structure of process networks

As a first step in the control structure design procedure, we systematize the process representation by making use of the ideas of *process networks* as a graph representation of the process flowsheet. A process network is defined by a number $j = 1, \ldots, \theta$ of well mixed homogeneous material regions connected by material and energy fluxes we will refer to as nodes, plus an extra region $j = 0$ which represents the environment. To each node j in the network, we associate a state vector $z_j \in \mathbb{R}^{c+1}$ of the form:

$$z_j = (n_j^1, \ldots, n_j^c, u_j)^T \tag{1}$$

where n_j^k represents the mole number of component k, u_j is the internal energy and c stands for the total number of chemical species. Graphically, each phase present in the process is represented by one circle denoting a node, and solid circles symbolizing the environment. Nodes and environment are connected by a set of θ convective fluxes which, for every node, we refer to as $f_j \in \mathbb{R}^{+c}$ and $p_j(f_j) \in \mathbb{R}^+$ for component and energy, respectively. In addition, we have the following relationship between mass and energy convective flows:

$$p_j(f_j) = \sum_{k=1}^{c} u_j^k f_j^k \tag{2}$$

with u_j^k being the energy density associated to component k in node j. Since energy is transported by convective flows, we also have that $p_j(0) = 0$. In the graphical representation, these mass and energy convective fluxes are denoted by solid and dashed arrows, respectively. Nodes in the network can also be interconnected by dissipative transfer fluxes collected in vectors $\varphi^k \in \mathbb{R}^{+d_c}$ (with $k = 1, \ldots, c$) and $\psi \in \mathbb{R}^{+d_u}$, where d_c and d_u stand for mass and energy dissipative transfer, respectively. In the network graphs, these dissipative fluxes are represented by solid and dashed double-head arrows for mass and energy, respectively. In order to exemplify this process network formalism, let us consider the system depicted in Fig. 1. This process includes a jacketed exothermic reactor, where reactant A is transformed to product B through the first order exothermic reaction $A \rightarrow B$, plus a flash unit where B is obtained as liquid product and reactant A is recycled.

The process flowsheet in Fig. 1 can be represented as the process network depicted in Fig. 2, where the reactor and its

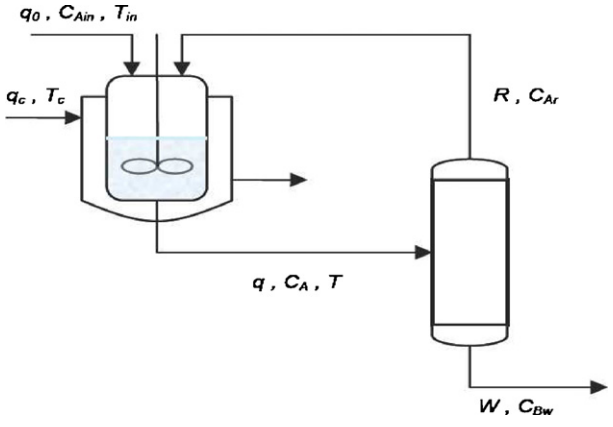

Fig. 1. Reactor-Separator process flowsheet (see notation list in Table 1). R, W, C_{A_r} and C_{B_w} represent the flowrates and concentrations of A and B in the recycle and final product streams, respectively.