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Optimal operation of heat exchanger networks with stream split: Only temperature measurements are required

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ABSTRACT

For heat exchanger networks with stream splits, we present a simple way of controlling the split ratio. We introduce the "Jäschke Temperature", which for a branch with one exchanger is defined as $T_J = (T - T_0)^2/(T_h - T_0)$, where T_0 and T are the inlet and outlet temperatures of the split stream (usually cold), and T_h is the inlet temperature of the other stream (usually hot). Assuming the heat transfer driving force is given by the arithmetic mean temperature difference, the Jäschke Temperatures of all branches must be equal to achieve maximum heat transfer. The optimal controlled variable is the difference between the Jäschke Temperatures of each branch, which should be controlled to zero. Heat capacity or heat transfer parameters are not needed, and no optimization is required to find the optimal setpoints for the controlled variables. Most importantly, our approach gives near-optimal operation for systems with logarithmic mean temperature difference as driving force.

1. Introduction

Global climate challenges and competition require efficient energy usage, and this typically implies re-using energy as much as possible. In the chemical and process industries, large amounts of energy can be saved by heat recovery in heat exchanger networks, which transfer energy in form of heat from a set of hot streams to a set of cold streams. By optimizing layout and operation of these heat exchanger networks, the overall consumption of natural resources for heating and cooling can be reduced considerably. In addition, this often results in significantly reduced operating costs.

The potential of heat exchanger networks for saving energy and costs has led to a large body of research, and most of the literature falls into one of two categories. The first category deals with the *design and synthesis* of heat exchanger networks (see e.g. Linnhoff and Flower, 1978; Linnhoff and Hindmarsh, 1983; Saboo and Morari, 1984; Saboo et al., 1985; Colberg and Morari, 1990; Yee and Grossmann, 1990; Gundersen et al., 1997; Furman and Sahinidis, 2002; Laukkanen et al., 2010). Most literature contributions belong to this category, where some likely conditions and scenarios are assumed, and the task is to find the optimal type, size, and structure of interconnections of the heat exchangers. Generally this results in large mixed integer optimization problems, and much of the literature addresses the issue of finding optimal solutions in an efficient way. Once the network structure and the size of the heat exchangers are decided, they either cannot be changed at all at a later point in time, or only at a high cost. The design step is therefore very important for the efficiency of the network.

The second category, where this work is placed in, deals with optimal *operation* of heat exchanger networks (Aguilera and Marchetti, 1998; Glemmestad et al., 1999; Rodera et al., 2003; Lersbamrungsuk et al., 2008). This category is complementary to the first one, as a good design does not imply good operation in terms of the benefits being actually achieved. In particular, finding optimal process operation strategies is important, because the conditions in the real plant generally differ from those assumed during the design stage. Even if the actual operating conditions are the same as assumed during plant design, Jensen and Skogestad (2008) showed that because of simplifying assumptions during design, like fixing the minimum temperature difference ΔT_{min} to 10 K, the optimal design point is often not the same as the optimal operating point. The contributions from this second category study how the available degrees of freedom, such as valves, bypasses and utility heaters, can be used to optimally match the real operating conditions and constraints. Although there has been some research activity in this area, there is still a need for simple methods to optimize operation of heat exchanger networks. The objective of

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this paper is therefore to provide an approach which leads to near-optimal operation of certain heat exchanger networks.

When implementing optimal operation in a process, such as heat exchanger networks, there are two fundamental model-based approaches which can be taken: Online optimization and offline optimization. In online optimization (Grötschel et al., 2001), the model is used to formulate an optimization problem, which is repeatedly solved online in a fast optimization software. The optimal input values obtained from the software are then applied to the plant. In this approach, the plant measurements are primarily used for adjusting model parameters, such that the model and the plant match. This approach may be implemented using a steady state model (Marlin and Hrymak, 1997; Lid et al., 2001), or alternatively a dynamic model (Grötschel et al., 2001). Implementing online optimization is relatively expensive due to the high costs of obtaining and maintaining a good process model, which can be optimized in real-time. However, if a good model is available, this approach can yield results which are very close to the true optimum. Due to the high costs, it is mainly implemented in cases where the immediate economic benefits are very high, such as refineries.

The alternative offline optimization approach exploits the structure of the optimal solution. This results in simple operating schemes which do not require online solution of optimization problems. The basic idea was first conceived by Morari et al. (1980), who write that "we want to find a function c of the process variables [...] which when held constant, leads automatically to the optimal adjustment of the manipulated variables, and with it, the optimal operating conditions." This idea has been followed in the paradigm of self-optimizing control, where such variables are found in a systematic manner, and in NCO-tracking, where these variables are the necessary optimality conditions (NCO) (Mathisen et al., 1992; Skogestad, 2000; Srinivasan and Bonvin, 2004; Lersbamrungsuk et al., 2008; Jäschke and Skogestad, 2011, 2012a). Although typically some degree of sub-optimality will have to be tolerated, these approaches are attractive in practice, because they are simple and easy to implement.

Considering the structure of the optimal solution, the steady state optimal operating point of heat exchanger networks without stream splits and with only single bypasses and utilities as manipulated variables, is characterized by being at constraints (Aguilera and Marchetti, 1998; Lersbamrungsuk et al., 2008), and can be described by a linear programming problem. In this case all degrees of freedom are used to specify target temperatures or are kept at constraints (e.g. bypass valves are used to control a target temperature, or are either fully open or fully closed). The problem of optimal operation is then reduced to finding and tracking the set of active constraints (Lersbamrungsuk et al., 2008), which often can be done without online optimization.

In this paper we study heat exchanger networks with stream splits, where the steady state optimal operating point is generally unconstrained. A simple example for such a system is shown in Fig. 1, where a cold stream F_0 is split into two branches, which each are heated individually by hot streams.

The operational objective is to maximize the total heat transfer, or equivalently to maximize the temperature after mixing, T_{end}. Here, the split fraction must be continuously adapted to match varying operating conditions such as changing inlet temperatures ($T_0, T_{h1,1}, T_{h1,2}$), flow rates ($F_0, F_{h1,1}, F_{h1,2}$), and heat transfer properties ($UA_{1,1}, UA_{1,2}$). In practice, these cases are either handled by an online optimization approach (Lid et al., 2001), when the potential savings are very high, or simply operated in an open-loop fashion, where the split ratio is set to some constant. Other ad-hoc solutions include isothermal mixing and controlling some outlet temperatures to a setpoint. These solutions are suboptimal.

The contribution of this paper is to present a simple method for optimizing operation of heat exchanger networks with stream splits. For each branch we define a "Jäschke Temperature", and near-optimal operation is achieved by adjusting the split between the branches in such a way that the Jäschke Temperatures of all branches are equal. The results have been submitted for patenting (Jäschke and Skogestad, 2012c). Nevertheless, the derivation is of interest for the scientific community and deserves the separate discussion provided in this paper. Our paper also fits nicely into this Morari special issue, because of his early important work on heat exchanger networks (Saboo and Morari, 1984) and optimal operation (Morari et al., 1980).

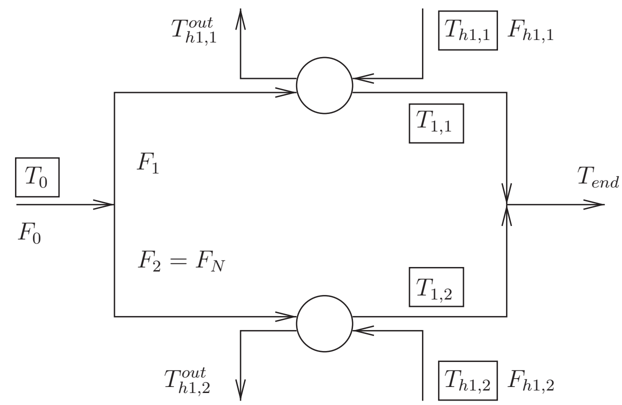

Fig. 1. Simple heat exchanger network with one split. The boxed variables are needed for obtaining the Jäschke Temperatures.

To obtain our results, we follow the general approach described by Jäschke and Skogestad (2012b): We set up a simple model, formulate the optimality conditions, and then eliminate the unmeasured variables from the optimality conditions. The obtained expression is a function of measurements only, and controlling it is equivalent to controlling the optimality conditions.

Note that the results in this paper also are applicable when a hot stream is split into parallel streams which are cooled down individually. To simplify the presentation, however, we present only the case, where the parallel streams are heated.

This paper is organized as follows: In Section 2 we provide relevant background material on optimality conditions for parallel systems, and Section 3 describes the network topology and heat exchanger model used in this work. The main results are presented in Section 4, and Section 5 contains some case studies to demonstrate the applicability of our results. Finally, the paper is closed with a discussion and conclusions in Sections 6 and 7.

2. Optimality conditions for parallel systems

Let us start by considering a smooth general optimization problem. After the active constraints are satisfied (e.g. by control) we can describe optimal operation as an unconstrained optimization problem,

$$\min_u \; J(u). \tag{1}$$

Here $u \in \mathbb{R}^{n_u}$ denotes the unconstrained degrees of freedom. To fully specify operation, we need as many controlled variables c as there are degrees of freedom u, $n_c = n_u$.

Consider now a system with the topology given in Fig. 2, with N parallel streams F_j which are branched off a given common feed stream F_0. The total operating cost J of the system is assumed to be the sum of the individual scalar costs J_j from each line j,

$$J = \sum_{j=1}^{N} J_j(F_j), \tag{2}$$