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Research Paper

Simplified dynamical input–output modeling of plate heat exchangers – case study

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HIGHLIGHTS

- Simplified dynamical modeling for plate heat exchangers was suggested.
- The optimization-based method for its tuning from the realistic measurement data was suggested.
- The suggested model was validated based on the measurement data.
- Stability and sensitivity analysis of the suggested model was provided.

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ABSTRACT

In this paper, the simplified dynamical modeling of PHEs (plate heat exchangers) is suggested and validated based on realistic measurement data. The concept combines general distributed parameter model of double-pipe heat exchanger with its spatial discretization based on orthogonal collocation method. This approach preserves the distributed parameter nature and nonlinearities of the unit with relatively low numerical complexity and high modeling accuracy. For the suggested model, the tuning procedure is suggested and modeling accuracy is validated for realistic experimental measurement data. The stability of the model (both structural and numerical) is addressed and sensitivity analysis and comparison with finite difference approximation are presented. The results show that the suggested modeling and tuning method is useful for practical applications.

1. Introduction

Nowadays, improving efficiency of industrial processes is considered as one of the most significant challenges for both control and process engineering. Many possibilities of reaching this goal were presented suggesting the concepts of such improvements. Some of them deal with economic impact of improvement in control. Bauer and Craig [1] presented the survey of methods used for assessing economic justification for applying new advanced process control systems to a process. Some of these methods are based on performance functions that incorporate economic aspects of variations of process variables around optimum operating point. Rhinehart et al. [2] presented the survey of advanced control methods that can be successfully applied in the industrial practice to provide improvement in control performance that can be linked to economic benefits. Yuan et al. [3] discussed the potential benefits resulting from simultaneous design of chemical processes and their control systems. This approach is based on optimizing performance function that combines decision variables defined for both process design and its control. Another important possibility for process efficiency improvement results from reducing energy consumption combined with high safety and environmental goals. For this purpose, heat exchange and distribution systems that constitute an important part of many industrial process must be properly designed and controlled. In his textbook, Kemp [4] provides the framework for pinch analysis methods that allow for minimizing energy consumption for chemical processes. Bonhivers et al. [5] proposed the method for heat exchange network (HEN) retrofit that provides significant energy savings. Semkov et al. [6] proposed the method for assessing potential heat energy savings by reducing waste heat and proved its usefulness in food industry. Jie et al. [7] noticed that operating cost of district heating systems can be minimized by reducing pumping and heat loss cost. The improvement in heat exchanger design that results in lowering operating cost can be also provided by proper adjusting design margins compensating for process uncertainties [8]. Morrison et al. [9] suggested the method for minimizing total annualized cost of HEN for non-continuous processes by its proper design (reducing total exchange surface area). Bakošová and Oravec [10] proposed the predictive control strategy for HEN that is based on simplified model-based approach. Isafiade et al. [11]

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also found the cost-effective synthesis of HENs as an important issue and they accounted for optimal design in the presence of multiperiod operating conditions including variations in process requirements and of stages of operation.

In industrial heat exchange systems, heat exchangers play an important role and their modeling is crucial for both optimal design and operating. Different types of heat exchangers are applied in (HENs) but plate heat exchangers (PHEs) are currently one of the most popular devices due to their high heat exchange efficiency combined with compact design, in comparison to conventional shell and tube heat exchangers [12,13]. This efficiency results from specific combination of gasketed corrugated metal plates that are pressed together to form the whole unit. The pattern of plates perforation and the internal flow configuration determine the performance of a particular PHE but at the same time, these construction details require complex and nonlinear modeling with a relatively large number of physical parameters that must be determined based on PHE assemblage. Consequently, every model should be case-dependent, which limits its generality.

Various works dealt with the subject of PHEs modeling based on their construction details. Starting from simple thermal modeling [14,15], interesting new works presenting different trends were also published. Thermal steady-state modeling of PHEs accounting for different plate and flow configurations was presented by Gut and Pinto [16]. The dynamical modeling where thermal dynamical equations describing PHE were coupled with material balance for milk fouling description can be found in [17]. 3D modeling and simulation of PHE based on computational fluid dynamics (CFD) was presented by Sammeta et al. [18]. The complexity of detailed modeling of heat transfer in PHE channels can be found in [19] where authors provided semi-empirical relationship describing heat exchange phenomenon accounting for channels geometry, flow velocity and physical fluid properties. These modeling approaches are very useful for optimal design and operating of new PHEs but their complexity is rather high, even if they assumed some simplifications. Usually, detailed case-dependent considerations were limited to steady-state conditions. At the same time, dynamical models were derived based on simplified assumptions (constant heat transfer coefficient, no heat loss, etc.) but they still accounted for PHE construction details. Consequently, they are useless for optimal design of high-layer control of existing HENs and for deriving regulatory-layer model-based control of single PHE operating in an existing process. For the latter, sometimes, the construction details for modeled PHE can be unknown or even if they are known, their inclusion in the model requires very hard modeling effort and finally leads to complex form. Thus, the motivation for this work was to suggest the general methodology, which provides the possibility of simplified input–output PHE modeling based only on input–output measurement data, without accounting for construction details. Additionally, it was assumed that the suggested method should be able to provide relatively accurate PHE modeling based on limited amount of measurement data. It is extremely important when modeling is carried out in industrial conditions where the measurements are collected from operating process and it is impossible to apply any extensive process excitation, especially leading to significant changes in operating conditions.

In such cases, the simplified modeling is required and one possibility is to apply simplified dynamical description in the form of the FOPDT (First Order Plus Dead Time) Laplace transfer functions, whose parameters can be easily identified from the process step response. This approach is very popular for approximating the significant dynamical properties of the industrial SISO (Single Input Single Output) processes [20]. However, this description is limited only for a single (control) forward path and its parameters must be time varying to represent the process nonlinearities resulting from changes in operating point. Moreover, it does not include the influence of disturbances, even if they are measurable. Thus, the general (case-independent) PHE modeling of a relatively simple form preserving its most important dynamical properties (such as distributed parameter nature, nonlinearities, etc.) was suggested. It is based on first principle modeling approach that is usually more accurate for wide variations of operating conditions [21,22]. At the same time, the number of model parameters should be minimized and the reliable method for identification of their values should be ensured based only on (limited) measurement data collected from a particular system. Such a model should also incorporate the influence of measured disturbances and describe the internal couplings between process inputs and outputs.

In this paper, such an approach to PHEs modeling is suggested based on conventional and widely accepted first principle modeling in the form of the partial differential equation derived from heat and mass conservation considerations. This approach is known for decades, not only for heat exchangers [23,24] but also for other dynamical systems, e.g. for distributed parameter pH processes [25], distributed parameter bioreactors [26], etc. It was widely applied in more or less complex and detailed forms for modeling the dynamics of double pipe heat exchangers [27], of helical baffle heat exchangers [28], etc. The form of this model is rather general and it describes the distributed parameter nature of heat exchange process and its nonlinearities. The concept suggested in this paper is based on this framework and it stands as the significant extension of the work of Fratczak et al. [29]. Namely, the very general and simplified form of the model was applied with only four model parameters lumping all unknown and case-dependent physical process parameters. Their values were identified from measurement data to ensure possibly highest input–output PHE modeling accuracy for wide range of operating conditions. Comparing to previous works of the authors, this paper addresses detailed model validation, sensitivity analysis and both structural and numerical stability considerations.

2. Simplified modeling of PHEs

The concept suggested in this paper for simplified modeling of PHE is based on the assumption that the unit is perfectly insulated and operated in conventional setup presented schematically in Fig. 1. The unit operates in the counter-flow mode with two circuits: one for hot water and the second for cold water. In both circuits, it is assumed that measurement data of flow rates F_1, F_2 [m^3/s], inlet temperatures T_{in1}, T_{in2} [°C] and outlet temperatures T_{out1}, T_{out2} [°C] are accessible on-line at certain sampling time τ_s [s].

Fig. 2 shows simplified schematic flow diagram for example symmetric PHE with parallel configuration with five plates *p1-p5* of length L [m]. Liquids flows in spaces (channels) between the plates formed by their perforation and gaskets between them. Heat ex-

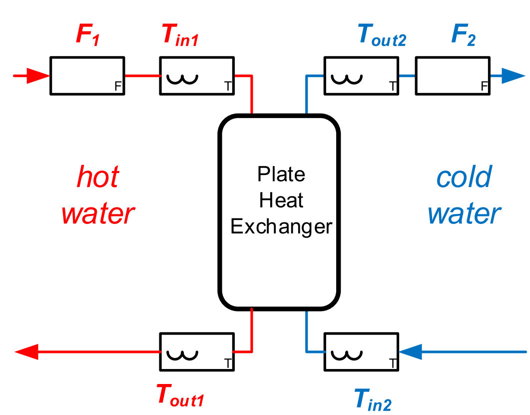

Fig. 1. Conventional application diagram of heat exchange system.