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Generation of an equipment module database for heat exchangers by cluster analysis of industrial applications

Martin Eilermann [a], Christian Post [a], Dorothea Schwarz [b], Stephan Leufke [b], Gerhard Schembecker [a,*], Christian Bramsiepe [a]

[a] TU Dortmund University, Department of Biochemical and Chemical Engineering, Laboratory of Plant and Process Design, Emil-Figge-Str. 70, 44227 Dortmund, Germany
[b] Evonik Technology & Infrastructure GmbH, Paul-Baumann-Straße 1, 45772 Marl, Germany

HIGHLIGHTS

- A new methodology for the generation of an equipment module database is proposed.
- 275 industrial applications of Evonik Industries AG are grouped in cluster analysis.
- Heat exchanger module is selected for each group of similar applications.
- 59% relative coverage achieved by 17 modules considering conservative constraints.
- 80% relative coverage achieved by 18 modules considering relaxed constraints.

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ABSTRACT

Module-based plant design opens up the opportunity for the (bio-)chemical industry to reduce lead times, which is crucial for future competitiveness. Equipment modules are designed once such that they can cover a wide range of process applications and conditions. The time-consuming equipment design step is replaced by selecting the most suitable equipment module from an equipment module database so that engineering work is reused. Although of central importance in module-based plant design, an applicable equipment module database has not been developed, yet. Therefore, it is the aim of this work to develop a methodology for the generation of shell and tube heat exchanger modules for an equipment module database. Existing industrial heat transfer applications are grouped by a hierarchical clustering algorithm. For each cluster of applications a representative heat exchanger is selected. A set of possible representatives is generated in a Sobol sequence from which a heat exchanger is selected to be the representative that covers most of the applications inside the cluster considered. The representative heat exchangers are stored in the equipment module database. The resulting 17 heat exchanger modules can cover 59% of the considered industrial applications despite their considerable diversity regarding conservative operating constraints.

1. Introduction

In times of globalization the chemical and biochemical industry is facing the challenges of varying customer demands, shorter product life-cycles and hence increasing volatile market developments (Buchholz, 2010). To cope with these challenges and thus to remain competitive, accelerated planning and design procedures are essential.

In conventional planning processes, the equipment is designed individually minimizing total cost with the aid of computer software, under consideration of functional requirements, operating constraints and industrial standards (Towler and Sinnott, 2013). A shell and tube heat exchanger could for example be designed using the Aspen Exchanger Design and Rating (EDR) tool considering the following constraints:

* Corresponding author.
E-mail addresses: Martin.Eilermann@bci.tu-dortmund.de (M. Eilermann), Christian.Post@bci.tu-dortmund.de (C. Post), Dorothea.Schwarz@evonik.com (D. Schwarz), Stephan.Leufke@evonik.com (S. Leufke), Gerhard.Schembecker@bci.tu-dortmund.de (G. Schembecker), Christian.Bramsiepe@bci.tu-dortmund.de (C. Bramsiepe).

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Nomenclature

ASME	American Society of Mechanical Engineers
calc	calculated
BEM	shell and tube heat exchanger type with bonnet front head (B), one pass shell (E) and fixed tube rear end head (M) (TEMA, 2007)
DIN	Deutsches Institut für Normung
EDR	Exchanger Design and Rating
Eq.	equation
est	estimation
HPLC	high pressure liquid chromatography
HX	heat exchanger
ID	inner diameter
in	ingoing
max	maximum
min	minimum
MINLP	mixed-integer nonlinear programming
OD	outer diameter
out	outgoing
P&ID	piping and instrumentation diagram
PDS	process data sheet
rel.	relative
req	required
SS	shell side
STHX	shell and tube heat exchanger
TEMA	Tubular Exchanger Manufacturers Association, Inc.
TS	tube side
$A_{CS,i}$	cross-sectional area (m^2)
A_{HT}	heat transfer area (m^2)
C	viscosity factor (–)
$c_{P,i}$	specific heat capacity (kJ $kg^{-1}K^{-1}$)
d_j	discrete design parameters
F	temperature correction factor (–)
f_i	feature
$\dot{m}_i$	mass flow rate (kg s^{-1})
p_i	pressure (Pa)
PR	pitch ratio (–)
$\dot{Q}$	heat flow rate (W)
$R_{f,i}$	fouling resistance (m^2 K W^{-1})
S	matrix resulting from Sobol sequence
T_i	temperature (°C)
ΔT_{lm}	logarithmic mean temperature difference (K)
ΔT_m	mean temperature difference (K)
U_0	overall heat transfer coefficient (W m^{-2} K^{-1})
v_i	velocity (m s^{-1})
$\dot{V}_i$	volumetric flow rate (m^3 s^{-1})
x_{ij}	transformed numbers in matrix S
X_{ij}	numbers in matrix S
η_i	dynamic viscosity (Pa s)
λ_i	thermal conductivity (W $m^{-1}K^{-1}$)
ρ_i	density (kg m^{-3})

- Thermodynamic constraint: Required heat transfer rate (Kuppan, 2013).
- Fluid dynamic constraints: Fluid velocities within certain ranges in order to prevent tube vibration, erosion and fouling (TEMA, 2007).
- Operation below a maximum pressure loss value (Kuppan, 2013).
- Heat exchanger dimensions according to standards, such as DIN or ASME.

This conventional design process involves several iteration steps. The question is, whether an individually designed apparatus is required for every application, or whether it is possible to cover a group of similar applications with one apparatus. This idea is embraced in the concept of module-based plant design. Equipment modules are equipment with fixed dimensions and are predesigned once such that they can cover a wide range of process conditions and applications. The time-consuming design step is replaced by selecting the most suitable equipment module from an equipment module database. Thereby, module-based plant design offers the opportunity to reuse engineering work of equipment which has previously been accomplished (Seifert et al., 2012; Hady and Wozny, 2012). Thus, the lead time can be reduced, which may offer a substantial economic benefit (Seifert et al., 2012; Lier and Grünewald, 2011).

Additionally, due to the simplified planning process, more process alternatives can be evaluated. Even the influence of detailed apparatus design can be considered. These alternatives can then be rated according to various criteria and for example the most energy efficient alternative can be selected.

Although of central importance in module-based plant design, an applicable equipment module database has not been developed, yet. Thus, there is a need for a methodology to intelligently design equipment modules, which are stored in an equipment module database. As an equipment module should cover various applications, conventional equipment design for one dedicated application is not possible. Nevertheless, the design parameters will be selected in compliance with standards. It is the aim of this work to present such a methodology for generating an equipment module database, suitable for industrial heat exchanger applications.

2. State of the art

Modular microstructured reactors are already applied in current practice. These reactors are assembled from components with standardized geometrical dimensions. Hence, they can be adapted to different chemical reaction processes and scaled-up with reduced risk. The production of early small scale campaigns is possible (Kockmann and Roberge, 2011; Ghaini et al., 2015; Borukhova and Hessel, 2013; Vural-Gürsel et al., 2012). Apart from microreactors, the integration of equipment modules in process development, however, is not that progressed yet.

An approach of a module-based planning process was given by Uzuner et al. A knowledge-based configuration of piping and instrumentation diagrams (P&IDs) from predesigned, flexible and hence modular P&ID-elements is presented. Thereby, the generation of P&IDs in the basic engineering phase can be accelerated. Nevertheless, the authors suggest an extension to the three-dimensional (3D) design process (Uzuner and Schembecker, 2012).

The transition from process simulations to 3D plant layout is investigated by Rottke et al. (2012). Based on layouts configured from predefined 3D-models of the equipment modules, more accurate cost estimations are possible. Exemplarily, modular high pressure liquid chromatography (HPLC) columns are designed by hand and considered in this context. Additionally, the authors emphasize the importance of defining applicable equipment modules for all unit operations and different processes (Rottke et al., 2012).

Goyal et al. apply cluster analysis in order to integrate data analysis in the generation of an equipment module database. It is stated that the consideration of customer demand in design and optimization of equipment modules is required. After clustering the randomly generated demand data, the dimensions of the equipment modules are determined by multiobjective optimization regarding