Computers and Chemical Engineering 35 (2011) 943–948

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Cell-based dynamic heat exchanger models—Direct determination of the cell number and size

Petar Sabev Varbanov[a], Jiří Jaromír Klemeš[a,*], Ferenc Friedler[b]

[a] Centre for Process Integration and Intensification – CPI^2, Research Institute for Chemical and Process Engineering, Faculty of Information Technology, University of Pannonia, Hungary
[b] Centre for Advanced Process Optimisation, Department of Computer Science and Systems Technology, Faculty of Information Technology, University of Pannonia, Hungary

ARTICLE INFO

Article history:
Received 1 October 2010
Received in revised form 8 December 2010
Accepted 17 January 2011
Available online 25 January 2011

Keywords:
Dynamic heat exchanger modelling
Cell models
Heat exchanger networks
Controllability

ABSTRACT

Large amounts of thermal energy are transferred between fluids for heating or cooling in industry as well as in the residential and service sectors. Typical examples are crude oil preheating, ethylene plants, pulp and paper plants, breweries, plants with exothermic and endothermic reactions, space heating, and cooling or refrigeration of food and beverages. Heat exchangers frequently operate under varying conditions. Their appropriate use in flexible heat exchanger networks as well as maintenance/reliability related calculations requires adequate models for estimating their dynamic behaviour. Cell-based dynamic models are very often used to represent heat exchangers with varying arrangements. The current paper describes a direct method and a visualisation technique for determining the number of the modelling cells and their size.

1. Introduction

The variability as well as the uncertainty of operating conditions of heat exchangers have been generally modelled in the framework of the concepts of flexibility, controllability, reliability and operability (Oliveira, Liporace, Araújo, & Queiroz, 2001; Skogestad & Postlethwaite, 1996; Sikos & Klemeš, 2010). Recent work in the field of dynamic operation and controller tuning of heat exchanger networks (Dobos & Abonyi, 2010; Dobos, Jäschke, Abonyi, & Skogestad, 2009) has illustrated the importance of using adequate and computationally efficient dynamic heat exchanger models. A very important issue is that heat exchangers are usually used in networks rather than standalone (Klemeš, Friedler, Bulatov, & Varbanov, 2010), which identify the computational efficiency as a key model property.

The appropriate use of heat exchangers under varying conditions requires adequate dynamic models. There are two general approaches to modelling the dynamics of a heat exchanger – distributed and lumped. These two model types have a number of features, which make them suitable for different applications. A comparison of the main features of the two approaches is given in Table 1.

The lumped cell-based models are more popular (Mathisen, Morari, & Skogestad, 1994; Roetzel & Xuan, 1999; Varga, Hangos, & Szigeti, 1995). There have been noticeable advances in the field of dynamic simulation of heat exchangers. Recent examples include: Luo, Guan, Li, and Roetzel (2003) model the dynamic behaviour of multi-stream heat exchangers; Konukman and Akman (2005) heat integrated plant; Ansari and Mortazavi (2006) present a distributed heat exchanger model; and Díaz, Sen, Yang, and McClain (2001), Varshney and Panigrahi (2005), and more recently Peng and Ling (2009) and Vasičkaninová, Bakošová, Mészáros, and Klemeš (2010, 2011) featuring a neural network based model. A prominent example of dynamic heat exchanger modelling from the food industry is presented by Georgiadis and Macchietto (2000) on the case of plate heat exchangers under fouling with milk. These models are quite complex and a little difficult to understand by process engineers. Most importantly, applied to heat exchanger networks, they feature high computational loads. The current paper is a step in direction of alleviating this problem.

Cell models can result in a potentially large number of equations, but the equations are very simple and the approach offers a uniform framework and modelling flexibility to accommodate any type of surface heat exchanger with any flow arrangement. The model complexity can be controlled by the number of cells, allowing a trade-off between the accuracy and the ability of the model to tackle large and complex process systems such as heat exchanger networks. Usually dynamic heat exchanger models (Roetzel & Xuan, 1999) are based on certain assumptions:

* Corresponding author at: Centre for Process Integration and Intensification – CPI^2, Research Institute for Chemical and Process Engineering, Faculty of Information Technology, University of Pannonia, Egyetem utca 10, 8200 Veszprém, Hungary. Tel.: +36 88421664; fax: +36 88624025.
E-mail address: klemes@cpi.uni-pannon.hu (J.J. Klemeš).

0098-1354/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compchemeng.2011.01.033

Nomenclature

Latin symbols

A_{CELL} heat transfer area for a modelling cell wall
$C_{p,C}$ specific heat capacity of the fluid in the cold cell tank
$C_{p,FLUID}$ specific heat capacity of a fluid
$C_{p,H}$ specific heat capacity of the fluid in the hot cell tank
$C_{p,W}$ specific heat capacity of the wall material
h_{HI} enthalpy of the hot inlet to a cell
h_{HO} enthalpy of the hot outlet from a cell
h_{CI} enthalpy of the cold inlet to a cell
h_{CO} enthalpy of the cold outlet from a cell
$h_{IN,HOT}$ enthalpy of the hot inlet to a heat exchanger
$h_{OUT,HOT}$ enthalpy of the hot outlet from a heat exchanger
$h_{IN,COLD}$ enthalpy of the cold inlet to a heat exchanger
$h_{OUT,COLD}$ enthalpy of the cold outlet from a heat exchanger
m_{COLD} mass flowrate of the fluid flowing through a cold cell tank and a heat exchanger
m_{FLUID} mass flowrate of the fluid flowing through a modelling cell tank
m_{HOT} mass flowrate of the fluid flowing through a hot cell tank and a heat exchanger
$mh_{C,CELL}$ mass holdup of the fluid in a cold modelling cell tank
$mh_{H,CELL}$ mass holdup of the fluid in a hot modelling cell tank
mh_{TANK} mass holdup of the fluid in a modelling cell tank
mh_{W} mass of the wall in a modelling cell
$N_{CELL,MIN}$ thermodynamically possible minimum number of modelling cells
Q_{CELL} the rate of heat transfer through the cell wall into or out from a modelling cell tank
$Q_{CELL,C}$ heat transfer rate for the cold tank in a modelling cell
$Q_{CELL,H}$ heat transfer rate for the hot tank in a modelling cell
t time
$T_{0,MIN}$, $T_{N,MIN}$ temperatures of the stream with the smaller heat capacity flow-rate in a heat exchanger, respectively, at the hot and the cold ends
T_{CI} temperature of the fluid at the inlet of a cold modelling cell tank
T_{CO} temperature of the fluid at the outlet of a cold modelling cell tank
$T_{FLUID,I}$ temperature of a fluid at the inlet of a modelling cell tank
$T_{FLUID,O}$ temperature of a fluid at the outlet of a modelling cell tank
T_{HI} temperature of the fluid at the inlet of a hot modelling cell tank
T_{HO} temperature of the fluid at the outlet of a hot modelling cell tank
T_{W} temperature of a modelling cell wall
U_{CELL} overall heat transfer coefficient for a modelling cell
v_{C} volumetric flowrate of the fluid in the cold cell tank
$V_{C,CELL}$ volume of the cold cell tank
v_{H} volumetric flowrate of the fluid in the hot cell tank
$V_{H,CELL}$ volume of the hot cell tank
V_{W} volume of the wall in a modelling cell
ΔT_{LM} logarithmic mean temperature difference for a heat exchanger

Greek symbols

$\alpha_{H,CELL}$ film heat transfer coefficient for the hot tank in a modelling cell
$\alpha_{C,CELL}$ film heat transfer coefficient for the cold tank in a modelling cell
ρ_{H} density of the fluid in the hot cell tank
ρ_{C} density of the fluid in the cold cell tank
ρ_{W} density of the wall material

(1) The heat transfer area is uniformly distributed throughout the heat exchanger unit.
(2) All thermal properties (film heat transfer coefficients, specific heat capacities) of the fluids and the exchanger wall are constant. The stream temperatures are considered to vary.
(3) The heat conduction along the axial direction (i.e. direction of the fluid flow) is negligible both within the fluids and within the wall.
(4) The wall thermal resistance to heat transfer is negligible. The effect of this assumption is equivalent to reducing the overall heat transfer coefficient. Therefore the imprecision resulting from this assumption can be compensated by an equivalent increase in the values of the film transfer coefficients.
(5) No heat is lost to the ambient through the exchanger casing.

The distributed models are derived from the general differential equations for heat transfer in a material medium. They are based on the consideration of an infinitely small differential element of the fluid stream or the wall. The resulting model is a set of few partial differential equations (one for the shell pass, two equations per tube pass) with differentiation with respect to time and the considered spatial coordinates (e.g. length). The basic model considers single pass apparatuses (one shell and one tube passes) with co-current and counter-current flows. Technically, it is possible to be extended for multi-pass heat exchangers and different flow configurations – including cross-flow (Roetzel & Xuan, 1999). However, the model becomes too complex and difficult to comprehend and solve.

The cell-based models combine a sufficient number of perfectly mixed model tanks, called cells, which makes the simulation results equivalent to those from a distributed model. Two mass and three energy balances are formulated for the elements of each heat exchange cell. All they take the form of ordinary differential equations with respect to the time.

Both described modelling approaches have their strong sides and associated problems. As a result, they are usually suitable for different applications. The distributed models recognise the continuous nature of the heat transfer both in time and in physical space. They can be solved relatively easy for simpler flow configurations such as single-pass co- and counter-current devices. Thus, they may be the preferred means to investigate the dynamics of heat transfer in general and for detailed studies of single heat exchangers.

However, applying distributed models to more complex heat exchangers and heat exchanger networks usually results in rather high computational burden. This is where cell-based models are generally stronger. Although cell models can result in potentially large numbers of modelling equations, these equations are very simple and offer a uniform modelling framework for any type of surface heat exchanger with any flow arrangement. Several authors (Mathisen et al., 1994; Varga et al., 1995) working in the field of process control and controllability prefer the cell modelling approach because of the modelling and computational simplicity. The main advantage of the model is that its complexity can be controlled by the user by adjusting the number of modelling cells. This allows exploiting the trade-off between the accuracy and the ability of the model to tackle large and complex process systems such as heat exchanger networks.

The computational advantages of cell-based models become clearer after considering the known techniques for solving the distributed models. The latter approach resorts to intensive numer-