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A calculation procedure for a heat exchanger and bypass equipment☆

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ABSTRACT

An efficient, technological solution for controlling the heat transfer performance of a heat exchanger is to install on process streams a bypass circuit, whose flow rate is determined in order to keep the outlet temperature of process fluids at target value. Control on outlet temperature is often necessary when working conditions undergo transients and modifications. In this manuscript, a calculation procedure for a heat exchanger and bypass equipment is described, along with relevant numerical model and solving technique. For developing the heat exchanger model in detail and validating the procedure against observed results, the specific case of a process waste heat boiler provided with a bypass is considered. The numerical model is based on mass, momentum and energy balance equations and is applied to a mono-dimensional and stationary type problem. The procedure can be conceptually extended to other specific applications and applied either to rating or design calculations.

1. Introduction

Control of heat transfer performance of heat exchangers is frequently of utmost importance in process industry. This is the case of exchangers installed upstream of a chemical reactor or an equipment for unitary operations like a fractionation column, which requires a feed at constant temperature for assuring proper chemical conversion or process yield. Fine control on process fluid temperature at the exchanger outlet is necessary when next operation is a catalytic synthesis, based on a precise activation temperature. Firstly, control is needed as transient conditions occur during start-up, shut-down and change of load operations; performance can be affected as well by disturbances on process parameters of inlet streams. Finally, turndown operating loads and fouling have usually a significant impact on heat exchanger performance. As a consequence, if a process control is not adopted, outlet temperature of fluids may be inadequate for next operation or even incompatible from a mechanical standpoint with downstream equipment. Installing a bypass on the heat exchanger is one of the most efficient solutions for its control and operability.

Typical process heat exchangers equipped with bypass for control of heat recovery are the feed-effluent heat exchangers (FEHE) used for pre-heating reactors or distillation column feed. Numerical models for such systems and their application to process control had been discussed in detail (Chen & Yu, 2003; Luyben, 2000); commercial simulation software can be an effective tool for investigating dynamics and flexibility of similar complex units (Paengjuntuek, Kiatpiriya, & Saikhwan, 2009). Modeling of tubular counter-current heat exchangers and relevant predictive and neural network predictive techniques for advanced process control on outlet temperature have also recently been discussed (Arbaoui, Verniéres-Hassimi, Seguin, & Abdelghani-Idrissi, 2007; Maidi, Diaf, & Corriou, 2009; Vasičkaninová, Bakošová, Mészáros, & Klemeš, 2010). Building cooling systems represent another interesting application involving heat transfer control of exchangers; for instance, regulation of thermal load of the chiller can be effectively obtained by adjusting cooling water flow rate by a valve installed on a bypass line (Franco, Sen, Yang, & McClain, 2003). Optimal operations and controllability of heat exchanger networks (HEN) are major topics in process industry and energy management. Swaney and Grossmann (1985) presented a pioneering work where concept of heat exchanger flexibility index was introduced; in another of the first works (Mathisen, Skogestad, & Wolff, 1992), criteria and numerical procedure for selecting bypass number and installation points in HEN were proposed. Effects on performance of HEN due to changes of known parameters were also studied by a sensitivity analysis approach (Kotjabasakis & Linnhoff, 1986; Ratnam & Patwardhan, 1991), which is useful for implementing safe operations and designing control schemes. Several numerical models for HEN are available in literature. A dynamic model for heat exchangers and relevant open- and closed-loop control technique applied to an HEN controlled by bypass manipulation was presented by Boyaci, Uzturk, Konukman, and Akman (1996); a detailed

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Nomenclature

a	speed of sound ($\mathrm{m\,s^{-2}}$)
c	local pressure loss coefficient (–)
C_P	specific heat ($\mathrm{J\,kg^{-1}\,{}^{\circ}C^{-1}}$)
D	diameter (m or mm)
E	specific total energy ($\mathrm{J\,kg^{-1}}$)
f	friction factor (–)
H	specific enthalpy ($\mathrm{J\,kg^{-1}}$)
H_C	heat transfer coefficient ($\mathrm{W\,m^{-2}\,{}^{\circ}C^{-1}}$)
M	molecular weight ($\mathrm{kg\,kmol^{-1}}$)
P	pressure (Pa or kPa)
r	radial coordinate (m or mm)
R	universal constant of gas ($\mathrm{J\,mol^{-1}\,{}^{\circ}C^{-1}}$)
R_F	fouling factor ($\mathrm{m^{2}\,{}^{\circ}C\,W^{-1}}$)
S	entropy ($\mathrm{J\,{}^{\circ}C^{-1}}$)
T	temperature (°C)
U	overall heat transfer coefficient ($\mathrm{W\,m^{-2}\,{}^{\circ}C^{-1}}$)
v	velocity ($\mathrm{m\,s^{-1}}$)
W	mass flow rate ($\mathrm{kg\,s^{-1}}$)
x	axial coordinate (m or mm)
y	molar fraction (–)
y'	mass fraction (–)
Z	compressibility factor (–)
Greek notation	
ϕ	generic quantity
ε	quantity for numerical convergence
μ	dynamic viscosity ($\mathrm{kg\,s^{-1}\,m^{-1}}$)
λ	thermal conductivity ($\mathrm{W\,m^{-1}\,{}^{\circ}C^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)
Subscripts	
b	refer to bypass
i	chemical species
s	refer to shell-side
t	refer to tube-side
w	refer to wall of exchanging tubes
contr	refer to sudden contraction at tubes/bypass inlet
enlar	refer to sudden enlargement at tubes/bypass outlet
in	refer to inlet
crit	refer to thermodynamic critical conditions
red	refer to thermodynamic reduced conditions

analysis about bypass effectiveness in smoothing operating disturbances on heat exchangers and HEN, along with relevant model for selecting bypass streams and achieving cost-optimization, can be found in Yan, Yang, and Huang (2001). Computational models based on linear programming techniques for on-line control and search of steady-state optimal operations of HEN equipped with bypass streams are available as well (Aguilera & Marchetti, 1998; Lersbamrungsuk, Srinophakun, Narasimhan, & Skogestad, 2008).

However, above works on modeling and control of heat exchangers and HEN are principally focused on process control techniques and cost optimization rather than process sizing of heat transfer equipment provided with bypass devices; consequently, no detailed models for heat exchanger and bypass systems appear available in current literature. Scope of the present work is therefore to make available a calculation procedure valid for a heat exchanger and bypass equipment, along with relevant numerical model; such procedure can be applied either to "rating" or "design" problems. Main operational and process control criteria, which can be considered of general application, are also discussed in the work.

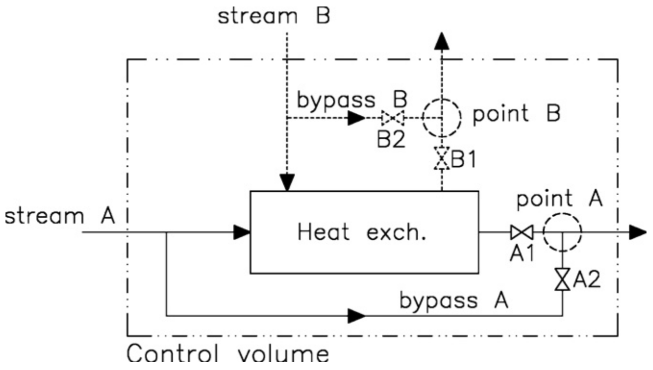

Fig. 1. Conceptual scheme for heat exchanger provided with bypass circuits.

For developing in detail the numerical model of the equipment and verifying computational results against plant data, a specific shell-and-tube heat exchanger equipped with bypass – a process waste heat boiler (WHB) – has been considered. Several industrial processes require cooling of a high temperature process fluid, practically gas, exiting from a furnace or chemical reactor; recovery of such a large enthalpy can be efficiently performed by means of a WHB that provides for cooling of gas by vaporization of water. WHB is usually installed upstream of chemical reactors or unitary operation equipment, therefore fine control of outlet temperature of process fluid is necessary. In steam reforming plants, a WHB is installed between reforming and high temperature shift reactors. In sulfuric acid plants, process gas exiting the sulfur burning furnace is cooled by a WHB before catalytic conversion to sulfur dioxide; again, in gas and oil plants, sulfur recovery by burning of acid gases is obtained by a furnace, WHB and Claus reactor train. Since no studies have been so far focused on the particular topic of process WHB equipped with bypass, this work also provides for a first model of a WHB.

A comprehensive description of sizing criteria for shell-and-tube heat exchangers can be found in engineering handbooks and standards (Kakac & Liu, 2002; TEMA Standard, 2007); these are applicable to WHB design as well. Nevertheless, the present WHB model is developed by means of differential equations representing mass, momentum and energy balances in stationary conditions, rather than by ordinary algebraic approach based on logarithmic difference temperature (Akman, Uygun, Uzturk, & Konukman, 2002; Boyaci et al., 1996; Varbanov, Klemeš, & Friedler, 2010). Such an equation-based modeling approach shows to be less correlation-dependant and more suitable for an extension of the model; on the other hand, some assumptions are introduced for reducing numerical complexity. Balance equations are applied to process gas and exchanging tube walls. Velocity and temperature profiles of gas are assumed to be fully developed and flat, and contribution of diffusive terms is considered negligible. Dependence on operating conditions for density, chemical–physical and transport properties is taken into account. As a result, the model for the WHB-bypass equipment is constituted of a system of non-linear differential equations, with non-constant coefficients; a numerical solution based on finite differences method is adopted. Operating data referring to a WHB installed in an industrial hydrogen plant have been used for verifying modeling results.

2. Operational criteria and calculation procedure

A heat exchanger provided with bypass on process streams is sketched in Fig. 1. Points A and B represent mixing points of bypassed flow with relevant main stream that has been heated/cooled across the exchanger; valves A1 and B1 are control valves mounted on main stream circuits, whereas valves A2 and B2