Journal of Cleaner Production xxx (2016) 1–8

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# A Total Site Heat Integration design method for integrated evaporation systems including vapour recompression

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ARTICLE INFO

*Article history:*
Received 23 February 2016
Received in revised form
3 June 2016
Accepted 7 June 2016
Available online xxx

*Keywords:*
Process integration
Pinch analysis
Total Site Heat Integration
Evaporation systems
Vapour recompression
Milk processing

ABSTRACT

This paper presents a new Total Site Heat Integration (TSHI) method for the design of integrated evaporation systems including vapour recompression that minimises energy use and/or cost objective functions. The design of integrated evaporation systems is a common industrial chemical and process engineering problem. The method defines a new hybrid Total Site Profile (TSP) as a key element of the new design method. This profile is a composite of nearby streams that may directly integrate with the evaporation system as well as stream segments from processes that require indirect integration via the utility system. The hybrid TSP plays an important role in the iterative optimisation of evaporation system design parameters including vapour recompression and evaporation load distribution to optimise objective functions such as total cost, total operating cost, and heat recovery. The new TSHI design method for evaporation systems is demonstrated using an industrial milk processing case study.


## 1. Introduction

Evaporation systems are commonly needed to concentrate multi-component liquid solutions, suspensions, and emulsions in the food and dairy, pulp and paper, petrochemical, chemical, and pharmaceutical industries. Evaporation systems normally achieve high levels of energy recovery by optimally cascading heat using various multi-effect arrangements (Khanam and Mohanty, 2010) as well as heat integration of evaporation/condensation loads with the heating and cooling needs of other processes (Smith, 2005). Integration of evaporation systems with vapour recompression technologies is a different approach for attaining high levels of energy efficiency, without increasing the number effects. The concept of vapour recompression in evaporation systems is to upgrade low-pressure vapour from an effect's evaporation-side to a higher temperature and pressure for re-injection on the condensation-side of the same or another effect. Mechanical Vapour Recompression (MVR) uses a blower to lift the pressure and temperature of a vapour flow. Thermal Vapour Recompression (TVR) uses a thermo-compressor in conjunction with steam injection for vapour recompression. Of the two techniques, a MVR blower requires higher capital investment, but can greatly reduce the number of effects and lowering overall energy use and operational cost (Hanneman and Robertson, 2005).

The field of Process Integration (PI) contains systematic methods, such as Pinch Analysis (PA), that can identify cleaner production solutions that minimise energy consumption of individual unit operations and processing sites (Dunn and Bush, 2001). PA, together with Total Site Heat Integration (TSHI) (Liew et al., 2014), are arguably the most universally applied PI techniques. With respect to evaporation systems, PA provides excellent visual tools, e.g. Composite Curves (CC) and the Grand Composite Curve (GCC), for understanding how an evaporation system can efficiently integrate with itself and with other processes on the same site, i.e. background processes (Linnhoff, 1998). Smith and Jones (1990) demonstrated that PA can form the basis for optimising the capital-energy trade-off during the process design and integration of multi-effect evaporation systems.

Westphalen and Wolf Maciel (2000) extended earlier methods to account for a fluid's changes in latent heat of vaporisation with temperature, to represent superheated and subcooled evaporator feeds on a temperature-enthalpy plot, and to optimise vapour bleed duties from each evaporator effect, which further minimised utility use, reduced the number of effects, and led to more favourable economics. Algehed and Berntsson (2003) looked at the TSHI of black liquor evaporators in the Kraft process by using medium-pressure steam and delivering some low-pressure steam back to

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http://dx.doi.org/10.1016/j.jclepro.2016.06.044
0959-6526/

**Nomenclature**

*Roman*

| | |
|---|---|
| $CP$ | heat capacity at constant pressure (kJ/[kg °C]) |
| $C$ | concentration (kg/kg) |
| $CC$ | heat exchanger capital cost ($) |
| $h$ | specific enthalpy (kJ/kg) |
| $k$ | ratio of specific heats |
| $\dot{m}$ | mass flow rate (kg/s) |
| $P$ | pressure (kPa) |
| $PR$ | thermo-compressor performance ratio ($kg_{vap}/kg_{steam}$) |
| $Q$ | duty (kW) |
| $R$ | gas constant (kJ/[kg K]) |
| $T$ | temperature (°C) |
| $TC$ | total cost ($/y) |
| $TCC$ | total capital cost ($/y) |
| $TOC$ | total operating cost ($/y) |
| $W_{comp}$ | work of compression (kW) |

*Greek*

| | |
|---|---|
| $\alpha$ | mass fraction of vapour upgraded |
| $\Delta$ | difference between two states |
| $\eta_o$ | compressor efficiency |

*Subscripts and Superscripts*

| | |
|---|---|
| * | shifted |
| *bleed* | vapour bleed |
| *cond* | condensation/condenser |
| *cont* | contribution |
| *eva* | evaporation |
| *exit* | exit stream |
| *feed* | feed stream |
| *fg* | fluid-vapour phase change |
| *l* | liquid |
| *min* | minimum |
| *P1* | low pressure |
| *P2* | high pressure |
| *s* | supply |
| *st* | steam |
| *t* | target |
| *upg* | upgraded low pressure vapour |
| *ut* | utility |
| *v* | vapour |

the steam utility system. Walmsley et al. (2016) applied similar PA techniques as Westphalen and Wolf Maciel (2000) in the analysis and possible retro-fit of existing milk evaporation systems that included vapour recompression.

A methodological gap that exists in PA and TSHI literature is a method for targeting and designing an integrated evaporation system where the background process GCC represents opportunities for both direct process–process and indirect process-utility integration. Past studies on integrated evaporation system design have focused on either direct process–process (Walmsley et al., 2016) or indirect process-utility integration opportunities (Algehed and Berntsson, 2003), not both simultaneously. One reason for this gap is the lack of single background heat demand profile that represents both opportunities for direct and indirect integration. This paper seeks to fill this gap by detailing the construction of a hybrid Total Site Profile (TSP).

Recent studies have mostly applied mathematical programming techniques for the optimisation of multi-effect evaporation systems. Druetta et al. (2014) optimised the design of a multi-effect evaporation system for seawater desalination using non-linear mathematical programming techniques. Galván-Ángeles et al. (2015) explored the design and cost trade-offs of integrating TVR into a multi-effect food evaporation system using mixed-integer non-linear optimisation. Han et al. (2015) applied the concept of self-heat recuperation theory in the design of single and multistage MVR evaporation systems for concentrating solutions with significant boiling point elevation.

The aim of this study is to develop a new TSHI method for the design of integrated evaporation systems including vapour recompression that minimises energy use and/or cost. This is achieved by maximising both direct process–process and indirect process-utility integration opportunities. The method uses a hybrid TSP as the basis for the new design method. This profile is a composite of streams nearby the evaporation system that may directly integrated as well as streams (or stream segments) from processes that require indirect integration via the utility system. The new profile plays an important role in helping identify how much the evaporation system can integrate across the site. It is also needed to improve the selection of which vapour recompression technology or combination of vapour recompression technologies are best applied to minimise energy use and/or cost. The new TSHI design method for evaporation systems is demonstrated by an industrial milk processing case study.

## 2. Methodology

A new design method for evaporation systems including vapour recompression is presented in Fig. 1. The method includes calculation of utility, heat recovery, area, and cost targets. The method assumes that vapour recompression is a possible component of the evaporation system. The first half of the method (left-hand side of Fig. 1) details the construction of hybrid TSP, which represents the background processes including possibilities for direct and indirect heat integration with the evaporation system. The second half of the method (right-hand side of Fig. 1) is specific to evaporation systems that require vapour recompression and describes a simple iterative optimisation approach.

### 2.1. Construction of a hybrid Total Site Profile

The left-hand side of Fig. 1 presents the procedure for generating a hybrid TSP. Many of these steps are common to past PA and TSHI literature.

Step 1: Evaporation system specifications

Important specifications for the evaporation system include: the dilute feed and concentrate flow rates, temperatures, and concentrations. For new builds, the specification of the general inputs/outputs of the evaporation system enables the design of upstream and downstream processes and unit operations.

Step 2: Determine background process stream data

Stream data is extracted from each background process. The stream data includes heat capacity flow rates, supply and target

Please cite this article in press as: Walmsley, T.G., A Total Site Heat Integration design method for integrated evaporation systems including vapour recompression, Journal of Cleaner Production (2016), http://dx.doi.org/10.1016/j.jclepro.2016.06.044