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Review

Advances in Process Integration research for CO_2 emission reduction – A review

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ABSTRACT

Carbon dioxide emissions coming from industrial, transport, service and business activities as well as methane and nitrogen oxides from agriculture are major greenhouse gases with high global warming potentials. Modelling tools for the optimal management and reduction of greenhouse gas emissions, in particular, carbon dioxide, have received growing attention. Concurrently, complementary graphical and visualisation tools for carbon dioxide targeting, design and planning based on Pinch Analysis have evolved in line with the developments of other Process Integration tools. The application of Pinch Analysis includes the conservation of resources including heat, mass, water, gas, materials, property, solid, and more recently, power. This paper provides a comprehensive review of the development of Process Integration insight-based graphical, algebraic and numerical tools for carbon dioxide emission reduction. The key focus of the review is on methodologies that are capable of making explicit assessment on, and quantify the impact of the use of the PI tool on CO_2 reduction, covering works from 2007 (when it was initially introduced) until year 2016. The review has been categorised into supply side energy and emission planning as well as demand side and end-of-pipe energy and emission management. The aim of the review is to provide researchers, industrial planners, policy-makers and energy managers awareness of the appropriate insight-based graphical, algebraic and visualisation Process Integration tools that are available for use for carbon dioxide emissions planning and reduction. Applications of such tools is expected to enhance their conceptual understanding of the problems and ultimately help them make better decisions during the planning and management of greenhouse gas emissions.

Contents

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1. Introduction

Growing global concerns on the environmental, social and economic impacts of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions have motivated the development and implementation of various tools and strategies for CO_2 emission mitigation (Fais et al., 2016). Systematic CO_2 emission planning and management via Process Integration can provide a sustainable alternative to control the continuous rise in anthropogenic CO_2 emissions (Khan et al., 2014) from various energy-intensive industries that include power plants, chemical plants, refineries, cement production, iron and steel industries. Process Integration (PI) based on Pinch Analysis is a set of methodologies for the conservation of resources and reduction of harmful emissions via integration of several parts of processes, coupled processes, processes within Total Sites (Klemeš et al., 1997) or industrial areas within a region (Perry et al., 2008). Progress on PI research and industrial implementation related to energy savings have been closely followed by the development of an integrated methodology for emission reduction (Friedler, 2010). PI has been developed beyond heat or power integration within the new dimensions of sustainability in the industry such as cleaner utilisation of fossil fuel, waste management and emissions reduction in utilising renewable and waste materials for the production of energy and goods (Varbanov and Seferlis, 2014).

PI based on Pinch Analysis has emerged as an insight-based tool for the design of energy-efficient process systems during the oil crisis of the 1970s (Linnhoff and Flower, 1978). Over more than forty-five years, Pinch Analysis has seen remarkable progress and has evolved into a suite of graphical, algebraic and numerical tools for the conservation of various types of resources (Klemeš et al., 2013). Fig. 1 shows the Pinch Analysis temperature versus enthalpy diagram that is popularly known as the Composite Curves. The Composite Curves provide a visual representation of the overall heat availability and requirements and the maximum possible heat recovery from a process. The Composite Curves are constructed by combining hot and cold streams of a process to yield the Hot Composite Curve (a single composite hot stream representing a process overall heat source) and the Cold Composite Curve - a single composite cold stream representing a process overall heat demand (Klemeš et al., 2010). The overlap between the Hot and Cold Composite Curves at the minimum allowable temperature difference (ΔT_{min}) represents the target for maximum heat recovery (MER) as shown in Fig. 1. As ΔT_{min} increases, the maximum heat recovery potential and the heat transfer area decreases. The term 'Pinch' represents the thermodynamic limit for the maximum heat recovery from a process. Qc and Q_h represent in Fig. 1 represent minimum cold utility and hot utility needed by the process.

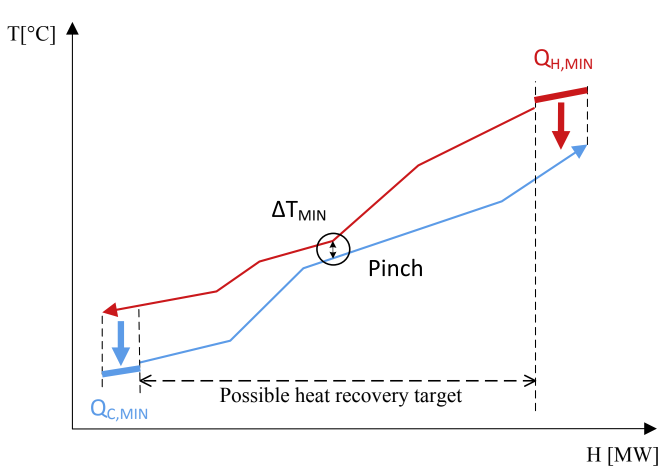

Fig. 1. Composite Curves for minimum energy targeting (Klemeš et al., 2010).

Subsequent generic Pinch Analysis methodologies developed for resources other than energy include Mass Pinch (El-Halwagi and Manousiouthakis, 1989), Water Pinch (Wang and Smith, 1994), Production Planning Pinch (Singhvi and Shenoy, 2002), Materials and Property Pinch (Foo et al., 2004), network design (Foo et al., 2005) and Gas Pinch Analysis (Foo and Manan, 2006). Earlier researchers working on Gas Pinch Analysis have developed the Oxygen Pinch (Zhelev and Ntlhakana, 1999) and Hydrogen Pinch Analysis (Alves and Towler, 2002) that are applicable to specific types of gas recovery networks.

PI methodologies have also been developed for resource minimisation, process optimisation and emission reductions Klemeš (2013). They include techniques for design of optimal hydrogen systems (Zhenmin, 2003), minimum water flowrates targeting for urban facilities and buildings (Manan et al., 2006), wastewater minimisation (Majozi et al., 2006), water network retrofit with regeneration (Tan et al., 2007), CO_2 emission constraint planning (Tan and Foo, 2007), targeting and design of water networks (Wan Alwi and Manan, 2008), inter-plant water integration (Chew and Foo, 2009), reduction of CO_2 footprint in chemical processes (Tjan et al., 2010), hydrogen networks targeting with purification and reuse (Zhang et al., 2011), design of energy-efficient batch process systems (Chaturvedi and Bandyopadhyay, 2012), energy allocation with CO_2 capture and storage - CCS (Shenoy and Shenoy, 2012), Power Pinch Analysis (PoPA) targeting (Wan Alwi et al., 2012), fuel switching (Tiew et al., 2012), CO_2 emission exchange (Munir et al., 2012), energy resource planning (Al-Mayyahi et al., 2013), property-based resource conservation (Saw et al., 2011), targeting CCS (Ooi et al., 2013a), power system planning, hydrogen allocation network (Bandyopadhyay et al., 2014), emission reduction in transport sector (Walmsley et al., 2015), GHG-Pinch Analysis for wastewater treatment plants (Kim et al., 2016), waste management Pinch Analysis (Ho et al., 2015), hydrogen network with purification reuse (Yang et al., 2016), CO_2 planning for unconventional gas field (Foo et al., 2016) and enhanced heat recovery for supercritical