Applied Energy 160 (2015) 172–184

Contents lists available at ScienceDirect

Applied Energy

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

# Maximising the recovery of low grade heat: An integrated heat integration framework incorporating heat pump intervention for simple and complex factories

J.H. Miah [a,b,*], A. Griffiths [a], R. McNeill [c], I. Poonaji [d], R. Martin [e], A. Leiser [f], S. Morse [b], A. Yang [g], J. Sadhukhan [b]

[a] *Nestlé UK Ltd, Rowan Drive, Fawdon, Newcastle Upon Tyne NE3 3TR, UK*
[b] *Centre for Environmental Strategy (CES), Faculty of Engineering & Physical Sciences, University of Surrey, Guildford GU2 7XH, UK*
[c] *Nestlé UK Ltd, Group Engineering, Haxby Road, York YO91 1XY, UK*
[d] *Nestlé UK Ltd, Group Technical and Production, 1 City Place, Gatwick, RH6 0PA, UK*
[e] *Nestlé UK Ltd, Group Technical and Production, Haxby Road, York YO91 1XY, UK*
[f] *Nestlé S.A, Corporate Engineering (CO-ENG), Avenue Nestlé 55, 1800 Vevey, Switzerland*
[g] *Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK*

## HIGHLIGHTS

- A new practical heat integration framework incorporating heat pump technology for simple and complex food factories.
- A decision making procedure was proposed to select process or utility heat integration in complex and diverse factories.
- New stream classifications proposed to identify and compare streams linked between process and utility, especially waste heat.
- A range of 'Heat Pump Thresholds' to identify and compare heat pump configurations with steam generation combustion boiler.

## ARTICLE INFO

*Article history:*
Received 27 January 2015
Received in revised form 5 September 2015
Accepted 7 September 2015

*Keywords:*
Heat pump
Low grade heat
Energy efficiency
Pinch analysis
Food factory
Food industry

## ABSTRACT

The recovery of heat has long been a key measure to improving energy efficiency and maximising the heat recovery of factories by Pinch analysis. However, a substantial amount of research has been dedicated to conventional heat integration where low grade heat is often ignored. Despite this, the sustainability challenges facing the process manufacturing community are turning interest on low grade energy recovery systems to further advance energy efficiency by technological interventions such as heat pumps. This paper presents a novel heat integration framework incorporating technological interventions for both simple and complex factories to evaluate all possible heat integration opportunities including low grade and waste heat. The key features of the framework include the role of heat pumps to upgrade heat which can significantly enhance energy efficiency; the selection process of heat pump designs which was aided by the development of 'Heat Pump Thresholds' to decide if heat pump designs are cost-competitive with steam generation combustion boiler; a decision making procedure to select process or utility heat integration in complex and diverse factories; and additional stream classifications to identify and separate streams that can be practically integrated. The application of the framework at a modified confectionery factory has yielded four options capable of delivering a total energy reduction of about 32% with an economic payback period of about 5 years. In comparison, conventional direct and/or indirect heat integration without heat pumps showed an energy reduction potential of only 3.7–4.3%. Despite the long payback, the role of heat pumps combined with an integrated search by direct and indirect heat exchange from zonal to factory level can provide the maximum heat recovery. The framework has the potential to be applied across the process manufacturing community to inform longer-term energy integration strategies.

---

* Corresponding author at: Centre for Environmental Strategy (CES), Faculty of Engineering & Physical Sciences, University of Surrey, Guildford GU2 7XH, UK.
*E-mail address:* j.miah@surrey.ac.uk (J.H. Miah).

http://dx.doi.org/10.1016/j.apenergy.2015.09.032
0306-2619/© 2015 The Authors. Published by Elsevier Ltd.

## 1. Introduction

In the past decade, the global dimensions of sustainability have directed the UK food industry – the largest manufacturing sector in the UK and a major energy user – to focus on energy efficiency as a top priority to reduce costs and environmental impact [1,37]. As a result, the UK food industry has embarked on a pathway to decouple energy consumption from production output. From 1990 to 2012, the energy consumption was reduced by 25.2% whilst increasing productivity by 5.1% [2,3]. Despite these efforts, the food industry will have to go significantly further to improve the energy efficiency of operations given the global long-term sustainability challenges up to 2050. For example, this includes energy security in the backdrop of rising industrial energy prices [4], increasing the food output by 60% on a finite planet [5], and reducing greenhouse gas emissions by 80–95% [6].

In the UK, the food industry represents 9625 food factories accounting for about 12% energy consumption by UK industry [7]. In comparison to the USA, there are 26,000 food factories accounting for about 8% energy consumption in the USA [8]. As such, developing an effective and practical approach to improving the energy efficiency of food factories can be a complicated endeavour given the diversity of the food products manufactured and the technologies that may be employed even within a single modern factory. There are various ways to improve the energy efficiency of food factories which vary in complexity, cost, risk and ease of implementation. A common pathway to reduce energy and greenhouse gasses is through the energy hierarchy [9] which is an ideal implementation process incorporating key measures that starts from the conservation of energy by reducing energy demand and operating equipment correctly, followed by the installation of energy efficient equipment, then the recovery and reuse of heat within processes by heat integration, and finally the replacement of the utility system with renewable energy which does not necessarily enhance energy efficiency but provides a sustainable source of energy. All of these measures can potentially contribute to energy reductions and it may lead to missed opportunities if one purses specific measures and ignore others. However, in practice the application of the recovery and reuse of heat within processes is not as wide as the potential promises [10], especially from the recovery of low grade heat up to 250 °C which is widely unutilised and is estimated to account for a potential cost saving of £70 million per annum in the UK [11,12]. This can be due to a number of factors which include; financing, disruption of technology, and lack of technology knowledge [13].

The recovery of low grade heat can be done by three approaches applied in two operating domains; process or utility [14,15]. The first approach is simple heat exchange by direct or indirect means following the laws of thermodynamics, the second is the upgrade of heat by a technological intervention e.g. heat pump to make the heat available for recovery by heat exchange [16], and finally the third is a systematic review of the heating and cooling system either at a targeted or whole factory level to design the most energy efficient heat exchange system known as Pinch analysis [14,15]. However, all of these approaches have limitations for the recovery of heat in a factory. For example, the first approach is simple and targeted based on an energy audit. As such, projects are typically developed based on economic returns which do not capture all the low grade heat across a factory due to a market and company undervaluation of energy. The second approach is also targeted but can be constrained by the heat pump design for example working fluids which limit the temperature of the low grade heat recoverable and heat discharged [17]. Also the integration of heat pumps has the potential to compromise product material quality due to toxic working fluids. The last approach requires a high level of resources e.g. time, money and knowledge to collect data and carry out an assessment where, despite the effort the final analysis can result in no recovery of low grade heat. This is because low grade streams typically fall outside of the interesting regions when the Pinch rules are applied, especially for streams below 60 °C. Despite this, Becker et al. [18] and Kapustenko et al. [19] have shown how heat pumps can be combined as part of a Pinch-based methodology. However, the scale of application is targeted and limited in scope. Recently, Miah et al. [20] overcame the scale of application issue by developing a practical comprehensive heat integration framework based on heuristics to maximise the heat recovery of food factories with diverse production lines by a combination of direct and indirect heat exchange from a zonal to factory level. However, one of the major limitations was the absence of the role of heat pumps in the Pinch-based approach to upgrade the low grade heat as a means to further enhance the energy efficiency of food factories.

Therefore, the research presented in this paper seeks to overcome the limitations of current approaches to heat integration of low grade heat by presenting a new heat integration framework. It builds upon earlier work on maximum heat recovery for industrial sites from zonal to factory level by a combination of direct and indirect heat exchange and incorporates low grade heat recovery by heat pump technology. Section 2 discusses low grade heat recovery by heat pump technology. This is followed by an overview and description of the heat integration framework in Section 3. The application of the framework is applied to a modified case study to show how the proposed framework works in practice in Section 4. A discussion on the framework and the case study are made in Section 5, before the conclusions are given in Section 6.

## 2. Heat pump

A heat pump is a device that takes in low-temperature heat and upgrades it to a higher temperature to primarily provide process heat or space heating [21]. However, it can also provide secondary cooling known as combined heating and cooling heat pumps. The source of low grade heat can either be waste heat expelled to the atmosphere or drain, and can also include heat that is currently cooled by a refrigeration plant. As such, it has the potential to replace a boiler or reduce the load requirement of a boiler and refrigeration plant for small-medium factories with capacities up to 10 MW. In addition, by reducing the load on refrigeration plants can reduce the factory water consumption as refrigeration plants typically employ forced wet cooling towers to cool the heat discharge to atmosphere. However, the capital cost of heat pumps is high in comparison to a conventional combustion boiler and typically impose long economic payback times. Despite this, there are different configurations of heat pumps with different COPs operating at different electricity costs that can be competitive with the aid of subsidies e.g. government grants like Renewable Heat Incentives (RHI) [22].

There are several commercial heat pump types available based on the vapour compression cycle or the absorption cycle [23,24], and new designs continue to emerge [25]. A simple mechanical heat pump arrangement with performance equations are shown in Fig. 1.

The working principle of a heat pump is as follows; the heat pump absorbs heat at a low temperature in the evaporator, consumes power when the working fluid is compressed and rejects heat at a higher temperature in the condenser. The condensed working fluid is expanded and partially vaporises. The cycle then repeats. The typical temperature lift can be anywhere up to 25 °C and is rarely higher as the capital & operating costs of compressors with high discharge pressures i.e. above 25 bar impose long