Applied Energy 229 (2018) 151–162

Contents lists available at ScienceDirect

Applied Energy

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

Energy modeling framework for optimizing heat recovery in a seasonal food processing facility

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HIGHLIGHTS

- Recipe driven energy model predicts energy consumption for food processing facility.
- Modular framework includes utility generators and accounts for local weather conditions.
- Nonlinear multi-objective optimization tool used to size a waste heat recovery system.
- Neural network representing cooling tower used to improve energy model computation time.
- Plant-level energy usage per kg product may be significantly reduced through optimization.

ARTICLE INFO

Keywords:
Energy efficiency
Food industry
Heat recovery
Optimization
Simulation

ABSTRACT

Societal, cultural and economic factors are driving food processors to reduce energy consumed per unit mass of food. This presents a unique problem because time variant batch processing using low to medium grade heat is common in food production facilities. Heat recovery methods may be implemented by food processors to reduce energy consumption; however, temporal variance in the process and utility flow require the development of a robust, easily implemented energy model to accurately determine system effectiveness and economic incentive. A bottom-up modular computational framework is proposed to model the energy consumption of a cannery. The model predicts that the cannery will require 612 kJ gas/kg product produced, which is within the ranges provided in previous literature. Results show that adding a globally optimized indirect heat recovery system will reduce the gas consumption by 6% annually. The proposed framework, used here to represent a cannery, may be adapted to many different types of food processing facilities. With a clear picture of energy consumption by device, and the ability to predict the impact of process modification or heat recovery, plant-level energy usage for food processing may be significantly reduced.

1. Introduction

As consumers have become more interested in sustainable energy, efficiency is becoming a foremost concern for many food processing companies. So much so that leading food processing companies are voluntarily adopting measures to reduce the amount of energy it takes to process foods. To this end, forty-two companies, including some of the largest food processors, have partnered with the U.S. Environmental Protection Agency (EPA) to improve their energy efficiency as part of the Energy Star Food Processing Focus [1].

Many different technologies are used by and available to food processors to offset primary electrical energy consumption, such as photovoltaics and wind generation. Alternatively, electrical cost may be reduced by shifting power consumption to off-peak hours. Zhu et al. developed an energy model for a refrigerated food warehouse and proposed integrating energy storage, calculating that operating costs could be reduced by 18% [2].

However, natural gas accounts for 52% of the energy used in the US food manufacturing industry [3]. More specifically, natural gas to generate steam accounts for 65% of the energy use in a typical cannery or 1977 $\frac{kJ}{kg}$ of product produced [4,5]. Steam is typically generated through fossil fuel combustion. Alternatives to fossil fuel have been studied, such as the anaerobic digestion of waste streams at canning facilities, and have been considered as a more sustainable means to produce steam. Hills presented real-world results from a 2-year laboratory digestion of tomato, peach and honeydew [6]. Raynal

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https://doi.org/10.1016/j.apenergy.2018.07.097
Received 28 March 2018; Received in revised form 10 July 2018; Accepted 20 July 2018

Nomenclature

A	area
Approach	$T_{w,out}-Twb_{a,in}$
C	fluid capacity
Ceq	nonlinear constraint equation
CT	cooling tower
c_p	specific heat at constant pressure (per unit mass)
Den	density
D_h	hydraulic diameter
E	effectiveness
F	correction factor
h	enthalpy (per unit mass)
k	thermal conductivity
HX	heat exchanger
$\dot{m}$	mass flow rate
N	number of increments used for discretization
NN	neural network
N_s	number of plates
NTU	number of transfer units
P	pressure
pws	saturation water vapor pressure
Pr	Prandtl
R	heat capacitance ratio
recirc	flowing thermal fluid
Range	$T_{w,in}-T_{w,out}$
Re	Reynolds
RH	relative humidity (as a percentage)
s	plate spacing
T	temperature (dry bulb, or bulk conditions)
Twb	wet bulb temperature
U	overall heat transfer coefficient
V	volume
v	specific volume
$\dot{V}$	volumetric flow rate
Ws	moist air saturation
η	efficiency
ϕ	relative humidity (as a fraction)
ω	humidity ratio

Subscripts

a	air
act	actual
amb	ambient
avg	average
brine	salt process water
can	can full of product
c	cold side
(d)	desired, or design, value
da	dry air
db	dry bulb
e	exit condition
f	liquid water (saturated)
g	water vapor (saturated)
h	hot side
hx	heat exchanger
in	inlet conditions
out	outlet conditions
pw	process water
recirc	recirculation Circuit
s	isentropic
sat	saturation conditions
tw	tower water
twr	tower water return
tws	tower water supply
w	water
wb	wet bulb
*zone*1	cooker cooler heating section
*zone*2	cooker cooler cooling section

increased solid removals and methane production by using a two-stage anaerobic digestion [7]. Batstone investigated the impact that granule size has on methane production in brewery and slaughter house waste streams [8]. Most recently Zhang considered a three-stage anaerobic to increase methane production [9]. Another approach to reducing total energy use is to maximize the efficiency of steam production. Freschi and Giaccone assessed the effectiveness of maximizing the efficiency of fuel usage by optimizing a trigeneration system within the food industry [10]. Both practices reduce fossil fuel, although pollutants (CO_2, NOx, etc) are still produced during combustion.

Perhaps a more economical and reliable way to reduce on-site emissions is to simply use thermal energy more efficiently within the facility. In particular, heat recovery focused on reducing the plant's total steam consumption will have the largest effect on reducing local emissions. Wang estimated that recovering and reusing heat before it is lost to a heat sink can save 8.96–11.95% of the total industrial fuel use in British Industry [11]. Waste heat recovery systems in American food factories have also been studied.

Heat recovery systems have been widely studied. An in-depth literature review by Miro found that the study of waste heat recovery systems in the industrial sector began in the 1970s but not until 2006 was the field of much interest. Miro attributed the revised popularity due to increased environmental interest [12]. One common approach to capturing low-grade waste heat is to transfer excess heat to centralized thermal storage tanks [13]. Duscha and Masica [14] and Wojnar and Lundberg [15] estimated that recovering waste heat into a thermal storage tank and reusing the thermal energy could reduce energy consumption in American food factories up to 6%. However, the optimization and design of the central thermal transfer systems are typically based on pinch analysis, mixed integer linear programming, or some combination of these approaches. A critical review by Klemes et al. describes the historical background of Pinch Analysis and Mathematical Programming for waste heat recovery system, sometimes called heat integration. Klemes et al. proposed that Mathematical Programming is best suited for problems that consider multiple objectives and/or a high number of optimization variables [16]. Tokos used mathematical programming, specifically mixed integer linear programming, for optimizing waste heat recovery systems at a batch processing brewery [17]. More recently Lee et al. used mixed integer linear programming for optimizing the heat recovery system but extended the optimization to include operational scheduling. Lee et al. chose mixed integer linear programming because pinch analysis ”may not be readily applied to cases with practical constraints on network design or cost consideration, are incapable of handling time as a variable” [18].

A recent EU funded road-mapping project to promote the integration of energy efficiency in manufacturing found that an easy to implement cost calculation tool is required [19]. Ideally, the tool would make the resource and energy-cost transparent to facility management [19], which will allow managers to make informed decisions on plant construction and design. One such model has been developed by Herman [20]. Hermans work provides a flexible and dynamic simulation model that uses discrete events to calculate energy use over time. The framework proposed here builds on Herman's model, integrating stream to stream heat recovery evaluation to facilitate plant management insight into to cost implications of implementing low-grade heat recovery within their facilities.