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Thermo-economic optimisation of industrial milk spray dryer exhaust to inlet air heat recovery

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ABSTRACT

This study reports a thermo-economic design optimisation of an industrial milk spray dryer liquid coupled loop exhaust heat recovery system. Incorporated into the analysis is the ability to predict the level of milk powder fouling over time and its impacts on heat transfer and pressure drop. Focus is given to a finned round tube, a bare round tube and a bare elliptical tube. Modelling results show that spray exhaust heat recovery is economically viable for the considered industrial case study. Based on the results, the best liquid coupled loop heat exchange system uses a finned tube heat exchanger to recover heat from the exhaust air with a face velocity of 4 m/s and 14 tube rows, which gives a net present value of NZ$2.9 million and an internal rate of return of 71%. The developed thermo-economic assessment method has the ability to cater to site specific needs that affect the utility savings and the capital cost for implementing exhaust heat recovery.

1. Introduction

Spray dryer exhaust heat recovery can typically increase dryer energy efficiency by 10–20 % [1], but it is complicated by the low heat transfer coefficient of air and the presence of powder particulates that may foul the heat exchanger surfaces. Several case studies on spray dryer heat integration for a range of industries from the 1980's, which was subsidised by the UK's energy efficiency demonstration scheme, showed 2–4 years as a typical payback and a steam savings of 10% [1,2]. In general, dryer exhaust heat recovery is applicable to a wide range of other industries. For example, Laurijssen et al. [3] demonstrated that dryer exhaust heat recovery for a conventional multi-cylinder dryer used in the paper industry plays a critical role in lowering thermal energy use by 32%. Han et al. [4] modelled a lignite-fired power station under variable load and proposed to use the hot flue for drying the incoming fuel as a means for heat recovery and boiler efficiency increases in the order of 1–2 %. Tippayawong et al. [5] analysed industrial longan drying practice to show that dryer heat recovery can increase thermal efficiency by 21%.

Increasing energy efficiency in milk spray drying is an important topic for New Zealand because the results of the New Zealand dairy industry heavily impacts the national economy. The installed capacity of milk spray drying in New Zealand reached an estimate of 300 t/h in 2013 with a consumption of around 29 PJ/y of thermal energy. Milk powders supply about 20% of New Zealand's exports. As a consequence, energy efficiency in milk powder production is therefore a prime concern for industry and the New Zealand government as a means of lifting national economic performance. Spray dryer exhaust heat recovery represents a great remaining opportunity for significantly increasing heat recovery in the milk powder production process. In the United States, many milk powder plants have installed exhaust heat recovery systems for preheating the inlet air. Besides heat recovery, another benefit for this practice is to minimise inlet dryer air humidity. For these plants, hot air for drying is generated using direct fired natural gas combustion, which combustion reaction increases the air's moisture content. Inlet air pre-heating reduces the fuel consumption, which reduces moisture in the air, which maximises the drying capacity of the air. New Zealand plants, however, favour indirect heating methods of the dryer air using steam or indirect gas fired air heaters. The additional benefit of lower inlet air humidity is not present in the New Zealand case.

The New Zealand dairy industry has been cautious to uptake spray dryer exhaust heat recovery. In the mid-1980's, the Plains Co-

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Nomenclature

Roman

A	area (m^2)
C	heat capacity flow rate (kW/°C)
C^*	ratio of minimum to maximum heat capacity flow rates for ε-NTU method
c_b	particulate concentration in air flow (kg/kg)
d_p	particle diameter (m)
h	heat transfer film coefficient (kW/°C · m^2)
j	Colburn j factor
NTU	number of transfer units
Nu	Nusselt number
ΔP	pressure drop (Pa or %)
P	temperature effectiveness
Q	heat duty (kW)
R	heat transfer resistance (°C · m^2/kW)
r	radius (μm)
t	time (s)
U	overall heat transfer coefficient (kW/°C · m^2)

Greek

Δ	positive difference between two states
ε	heat exchanger effectiveness
τ	time constant (s)
ϕ	probability

Subscripts/superscripts

c	cold stream
f	fouling
F	frontal
h	hot stream
HX	heat exchanger
i	impact
l	loop
min	minimum
o	overall
p	pass
r	recovery
s	sticking
tot	total
tube	heat exchanger tube
w	wall

Op Dairy Ltd factory installed a glass tube air-to-air exhaust heat recovery system. However, energy surveys of its performance showed that heat recovery levels decreased by as much 40% after 13 h of operation due to milk powder fouling. In 2008, a New Zealand South Island dairy factory built a new state-of-the-art dryer, which was also the world's largest milk dryer at the time, and had plans to install a liquid coupled loop exhaust heat recovery system. The exhaust heat exchanger was built but never installed due to concerns over milk powder fouling causing disruptions to plant production. Since that time an additional twelve milk powder spray dryers have been built in New Zealand all without exhaust heat recovery, which evidences that exhaust heat recovery is not standard industry practice in New Zealand.

Within the field of Process Integration, PA (Pinch Analysis) is an established methodology originally proposed by Linnhoff et al. [6] for targeting heat recovery and utility use for industrial processes using Problem Tables and Composite Curves, and developing cost-effective heat exchanger networks. Recent PA studies on milk powder production have shown that to significantly increase heat recovery, heat is required to be recovered from the exhaust air for either intra-plant [7] or inter-plant heat integration [8]. Selection of soft target temperatures in the milk powder plant such as the final temperature of the exhaust air critically affects the shape of the Grand Composite Curve and the location of the Pinch temperature [9]. The exhaust air temperature of milk spray dryers is typically 65–85 °C. Walmsley et al. [7] showed there is no additional steam savings value in recovering dryer exhaust heat below the temperature range of 50–55 °C based on a minimum approach temperature. Atkins et al. [10] modelled the benefit of spray dryer exhaust heat recovery using a liquid coupled loop heat exchanger system to the overall heat recovery in the milk powder process. However their study was confined to the heat transfer characteristics of the liquid coupled loop heat exchanger system. This study furthers the work of Atkins et al. [10] to look closely at the fouling and cost elements of installing exhaust heat recovery systems in industry.

This paper reports the application of a comprehensive thermo-economic assessment tool for modelling a dryer exhaust-to-inlet air indirect heat recovery system to maximise key economic indicators such as NPV (Net Present Value) and IRR (Internal Rate of Return). The model quantifies the trade-off between heat transfer, pressure drop and fouling in terms of cost so that an optimisation can be performed. Literature correlations for the Colburn j factor and Fanning friction factor f of various heat transfer surfaces from Kays and London [11] form the basis for estimating the overall heat recovery of the system. An estimate of the fouling on the heat exchanger surface based on the milk powder deposition model presented by Walmsley et al. [12] is incorporated into the thermo-economic analysis. The comprehensive model is anticipated to demonstrate whether or not milk spray dryer exhaust heat recovery can be economic for a case study of a New Zealand dairy plant. In the general, the tool developed in this optimisation study has the potential to be applied to any dairy plant.

2. The milk spray dryer exhaust heat recovery system design problem

The design challenge and potential optimisation associated with spray dryer exhaust heat recovery can be expressed diagrammatically as presented in Fig. 1. The up-side down triangle represents the possible exhaust heat exchanger solutions. On the one hand, exhaust heat exchangers with a greater number of tube rows can

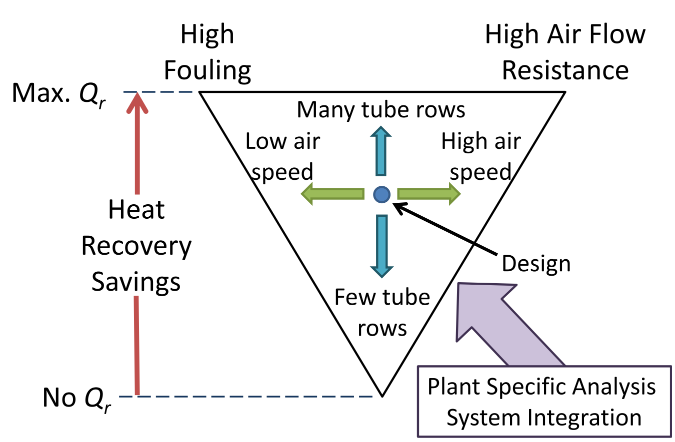

Fig. 1. The exhaust heat exchanger design challenge.