CHEMICAL ENGINEERING TRANSACTIONS

VOL. 39, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong
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ISBN 978-88-95608-30-3; **ISSN** 2283-9216

DOI: 10.3303/CET1439244

Thermo-Economic Assessment Tool for Industrial Milk Spray Dryer Exhaust Heat Recovery Systems with Particulate Fouling

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This study reports the development of an Excel spreadsheet based tool for performing a thermo-economic assessment of milk spray dryer liquid coupled loop exhaust heat recovery. Incorporated into the tool 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 finned round tubes, and round and elliptical tube geometries without fins. Modelling results show that spray exhaust heat recovery is economically viable for the industrial case study considered. 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 NPV of NZ$2.9 million and an IRR of 71 %. The tool has the ability to cater to site specific needs that affect the utility savings and the capital cost for implementing exhaust heat recovery. It is anticipated that this tool will provide confidence to the New Zealand dairy industry to uptake exhaust heat recovery.

1. Introduction

Spray dryer exhaust heat recovery can typically increase dryer energy efficiency by 10 – 20 % (Reay, 1982) but is complicated by the low heat transfer coefficient of air and the presence of powder particulates that may foul heat exchange surfaces. In New Zealand (NZ), spray drying is used to produce over 250 tonnes of milk powders per hour at full capacity while requiring around 24 PJ/y of thermal energy. Milk powder are about 19 % of NZ's national exports. Energy efficiency in milk powder production is therefore a prime concern for industry and the NZ government. The New Zealand dairy industry has been cautious to uptake spray dryer exhaust heat recovery. In the mid-1980's, the Plains Co-Op Dairy Ltd factory installed a glass tube air-to-air exhaust heat recovery system. However, energy surveys of its performance showed heat recovery levels decreased by as much 40 % after 13 h of operation due to milk powder fouling. In 2008, the Edendale 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 is evidence that exhaust heat recovery is not standard industry practice in New Zealand.

Recent Pinch Analysis studies have shown that, to significantly increase heat recovery in milk powder production, heat is required to be recovered from the exhaust air (Walmsley et al., 2013a). Selection of soft target temperatures in the milk powder plant critically affects the shape of the Grand Composite Curve and the location of the Pinch temperature (Walmsley et al., 2012a). Figure 1 explains the design challenge and potential optimisation associated with spray dryer exhaust heat recovery. 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 recover more heat but this increases both pressure drop and fouling. Fewer tube rows recover less heat with lower fouling and pressure drop. The air face velocity on the heat exchanger is also important and may be manipulated by changing the duct dimensions. High air velocities

Please cite this article as: Walmsley T.G., Walmsley M.R.W., Atkins M.J., Neale J.R., 2014, Thermo-economic assessment tool for industrial milk spray dryer exhaust heat recovery systems with particulate fouling, Chemical Engineering Transactions, 39, 1459-1464 DOI:10.3303/CET1439244

reduce fouling and improve heat transfer but also increase pressure drop. Lower air velocities have the opposite effect. Finding the right balance between heat recovery, fouling, and pressure drop is chiefly governed by the number of tube rows of the heat exchanger, the face velocity and the geometry of the heat exchanger surface. These parameters are important degrees of freedom that may be manipulated to maximise the economic benefit of an exhaust heat recovery project.

This paper reports the development of a thermo-economic assessment tool for modelling a dryer exhaust-to-inlet air indirect heat recovery system so that key economic indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) may be maximised. Incorporated into the tool is an estimate of the fouling on the heat exchanger surfaces based on the milk powder deposition model presented by Walmsley et al. (2014). Literature correlations for the Colburn j factor and Fanning friction factor f of various heat transfer surfaces are applied to model the heat exchanger system. In the tool, user defined parameters include heat exchanger geometry, heat exchanger surface type, exhaust and inlet air conditions including the particulate concentration, utility prices, and capital cost equations.

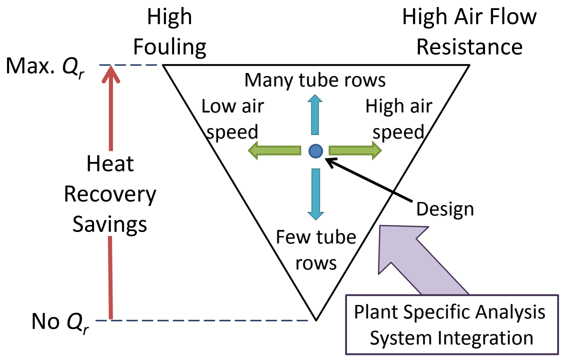

Figure 1: The spray dryer exhaust heat exchanger design challenge

2. Method for modelling indirect exhaust heat recovery system

The performance of an inlet air – exhaust air multi-pass liquid coupled loop heat exchange system has been modelled in a spreadsheet tool using the effectiveness – number of transfer units method. Heat transfer and friction factor correlations have been formulated using the tabulated data presented in Kays and London (1998) for staggered finned tube banks and the data in Walmsley et al. (2012b) for bare circular and elliptical tube geometries. The liquid loop flow is determined using the flow rate optimisation equation of Holmberg (1975).

Figure 2 is a flow diagram of how the fouling build up was predicted. After entering the required inputs, the spreadsheet calculates the overall system duty and estimates the air temperature profile within the exhaust heat exchanger. The temperature profile is used to calculate a critical impact angle using the deposition model of Walmsley et al. (2014) for each combination of tube row and particle size, which may be translated into a probability of sticking assuming a uniform particle impact distribution across the frontal face of a tube. The probability of sticking is the probability that a particle which impacts a tube will stick. The probability of impact is the probability that a particle will impact a tube. The probability of impact is assumed constant and equal to one minus the frontal free-flow area.

The product of the probabilities of impact and sticking give the percentage of particle mass entering a row that will deposit. This process of calculating the mass deposited is repeated for each combination of particle size fraction and tube row within a single time-step.

Fouling on the tube is typically concentrated at the front of the tube for milk powder particles as was demonstrated by Walmsley et al. (2013b). But the effect of the fouling build-up on heat transfer resistance of foulant, R_f, is estimated by assuming the foulant acts as a uniform resistance layer. The effect of fouling on friction factor f is estimated from the experimental deposition data of Walmsley et al. (2013b). For each new time-step, the performance of the heat recovery system and the exhaust heat exchanger temperature profile is recalculated. Once the run-time is complete, the model uses the cumulative heat recovery savings and costs to estimate the payback, NPV and IRR for the system.

The spreadsheet tool incorporating the fouling model required 2.5 h on average to complete the analysis for one heat exchanger design using a time step of 5 h for a total cycle of 672 h (or 4 weeks). The fouling model was computed on an Intel^{TM} Core i7 3.4 GHz processor. Test cases were used to determine the appropriate time step as to minimise its impact on the final solution.

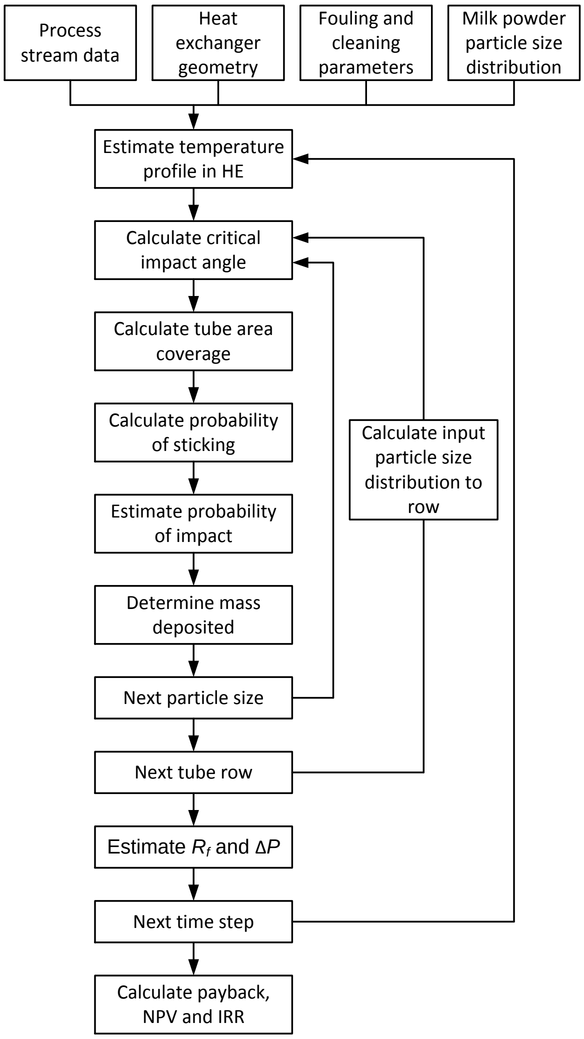

Figure 2: Heat exchanger fouling model flow diagram

The fouling build-up model makes several simplifications and assumptions. Uniform distribution along the length of each tube is assumed although in practice the particle distribution, which is often related to the airflow distribution, may be mal-distributed causing a non-uniform profile along the length of a tube. Deposition is also likely to be heavier near the heat exchanger outer walls as shown in the experimental work by Walmsley et al. (2013b). The probability of impact is constant for all rows and particle sizes. The probability of sticking has no respect for the surface condition and assumes the probability of a particle sticking to the tube wall is similar to a particle sticking to a particle. This simplification is supported by the work of Nijdam and Langrish (2005), who found pre-coating the inside of a dryer with powder had little effect on the rate of deposition build-up.

The literature and industrial documentation has very few capital cost estimation equations for finned tube heat exchangers, which differentiate between surfaces with different fin pitches and tube or fin thickness. As a result the costs of the heat exchangers have been estimated using two different methods. Method A is based on calculating the total mass of stainless steel and aluminium required to make the heat exchangers multiplied by individual forming factors that reflect how easy a material will shape. Added to the material and forming costs is the cost of welding the heat exchanger together and the cost of finning a tube. The sum of the various cost components relating to the construction of the heat exchanger is multiplied by a Lang factor of 3.5 (Bouman et al., 2005). Heat exchanger cost method B is based on the total area of the heat exchanger using the equation presented in Walmsley et al. (2013a).

3. Exhaust heat recovery industrial case study

The case study for modelling exhaust heat recovery is taken from Walmsley et al. (2013a). The exhaust air temperature is 75 °C with a humidity of 48 g/kg before heat recovery flowing at 153 kg/s on a dry air basis. The inlet air is drawn in at 15 °C on average with a humidity of 10 g/kg at 117 kg/s on a dry air basis. The exhaust air flow includes air flow through the dryer and fluidised beds whereas the inlet air flow is only for the dryer. In the analysis, a steam cost of $ 45 /MWh and an electricity price of $ 120 /GWh are used. The plant operates for 5,000 h/y and the dryer is washed every four weeks. At a minimum it is hoped that the exhaust heat exchanger will not require cleaning while the dryer is on product. Project economics are calculated using a typical industrial discount rate of 15 % and an accounting period of 10 y. Utility prices are assumed to rise at a constant rate of 5 %/y.

3.1 Modelling heat exchanger performance with fouling

Heat exchanger performance has been modelled for a four week period and fouling build-up and its associated effects has been estimated. The size and geometry of the inlet heat exchanger is fixed in the modelling with 12 rows of finned tube and a face velocity of 4 m/s. Figure 3 plots one case where the exhaust exchanger has 14 tube rows and a face velocity of 4 m/s. Tube geometries examined are circular finned tube (CF), circular bare (CB), and elliptical bare (EB). With no fouling, the finned round tube option for the exhaust heat exchanger recovered 3.2 MW, which is equivalent to a 14.4 % reduction in steam use for the main dryer air heater. The duty of the finned tube exhaust exchanger system fell to 3.0 MW at the end of the dryer production cycle. The finned round tube had the greatest amount of deposition resulting in an 8 % reduction in heat recovery, which is similar heat transfer reductions experienced in boilers (Stehlík, 2011), and an increase in pressure drop for the exhaust exchanger of 5 %, which is very modest. The bare round tube exhaust heat exchanger began with a duty of 2.7 MW, which fell to 2.6 MW at the end of the dryer run, and a pressure drop increase of 2 %. The elliptical bare tube experienced very little fouling resulting in only a small change to its heat recovery and pressure drop.

The exhaust exchanger with bare round tube recovers 17 % less heat than with finned round tube. Fouling on the bare round tube is expected to be less than for the finned tube because the average temperatures experienced in the exhaust heat exchanger are higher due to less heat recovery compared to the finned round tube. The elliptical bare tube has a 41 % lower pressure drop and a 3 % higher heat recovery compared to the bare round tube. The elliptical tube is naturally low fouling as by Walmsley et al. (2013b) for milk powder deposition.

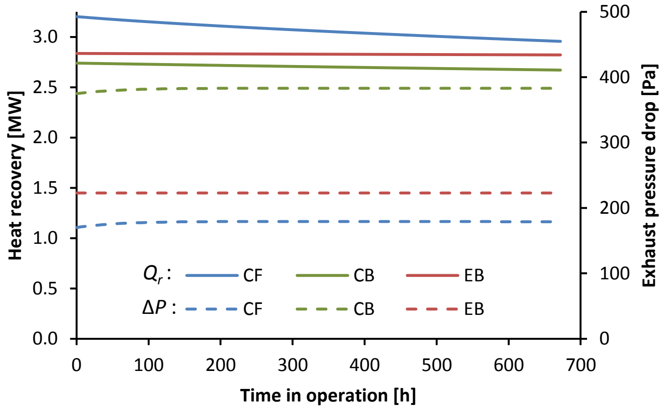

Figure 3: Estimated heat recovery and pressure drop for a period of four weeks

3.2 Optimisation of the liquid coupled loop heat exchanger system

Exhaust heat recovery performance including fouling has been modelled for the three tube geometries, number of tube rows in the exhaust exchanger (4 – 40), and face velocities for the exhaust heat exchanger (2 – 8 m/s). In total over 25,000 time steps were modelled and the economics of the exhaust heat recovery system was analysed in terms of NPV and IRR based on average heat recovery and pressure drop values. Figure 4 plots the results for a finned round tube, bare round tube and elliptical round tube using the number of tube rows in the exhaust exchanger as the independent variable on the x-axis for Figure 4a and the exhaust air final outlet temperature for Figure 4b. Figure 4a shows it is possible to design an economically favourable heat recovery system with payback times of about two years with IRR values greater than 50 % with an NPV of nearly NZ$ 3 million. The inlet heat exchanger has 12 tube rows, which is an additional degree of freedom, which optimisation is not presented. For Figure 4 the face velocity of the heat exchanger is set at 4.0 m/s. Each point in Figure 4 takes into account fouling which overtime lowers heat recovery and increases pressure drop.

Based on IRR a designer would select 4 – 6 tube rows for the exhaust exchanger whereas NPV indicates 12 – 14 tube rows is most profitable in the long run. This difference is important because IRR gives a good indication of the short-term payback of a project and NPV focuses on the long-term profit. As expected the finned tube exhaust heat exchanger offers better IRR and NPV values compared to the bare tubes. The finned tube arrangement was selected over the other finned tube geometries in Kays and London (1998) because of its high Goodness factor (*j*/*f*).

Face velocity of the exhaust air heat exchanger is another important design parameter. Fluid velocity is often a parameter that is manipulated to reduce heat exchanger fouling at the expense of increased pressure drop. Figure 5 plots the peak IRR and NPV values for the three heat exchanger geometries. In all cases the number of rows to achieve the peak IRR value compared to the peak NPV value is different. IRR analysis suggests a face velocity of about 6 m/s is advantageous whereas the NPV values support the selection of 4 m/s. Some dairy plants in New Zealand have a minimum threshold of an IRR of 50 % for an energy project to be actioned. 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. For this system the NPV is NZ$2.9 million and an IRR of 71 %.

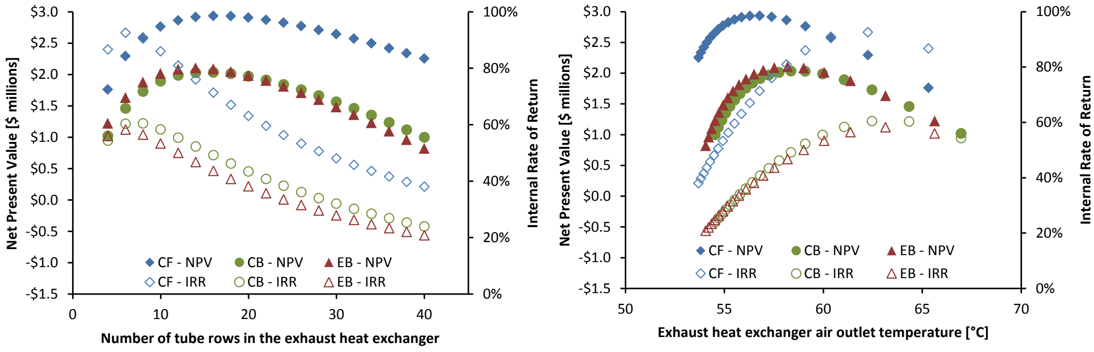

Figure 4: (a) Left – NPV and IRR values for a range of a number of exhaust tube rows; (b) Right – NPV and IRR for a range of exhaust outlet temperatures

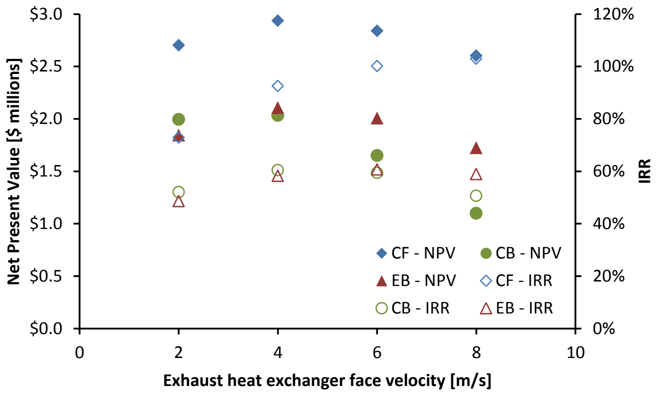

Figure 5: Heat exchanger face velocity versus the peak NPV and IRR values

4. Importance of site selection for dryer exhaust heat recovery

The economics for dryer exhaust heat recovery are highly site specific. The operation, equipment, and construction for each milk powder plant and spray dryer in NZ are slightly different. As a result these several site specific details need to be considered to accurately determine the economic profitability of an exhaust heat recovery system. Important factors to consider in a site specific analysis include: (1) exhaust air temperature and humidity (65 – 85 °C), (2) inlet air temperature and humidity to the dryer, (3) inlet and exhaust fan capacity, (4) existing pre-heaters using utility, (5) existing heat recovery to dryer inlet air, (6) re-usable existing ducting, (7) price of energy, (8) annual operating and production hours, (9) space constraints, (10) inlet air heater bottleneck, (11) powder-air separation technology e.g. cyclones and/or bag filters, and (12) good attitude to change. As identified in the above list, the dryer exhaust air temperature and the inlet air temperature for a particular site will strongly affect the economics. Preliminary investigation suggests for an exhaust temperature of 65 °C, an exhaust heat exchanger with fewer rows gives a peak NPV.

5. Conclusions

Exhaust heat recovery is economically justifiable for the typical industrial cases study with an exhaust temperature of 75 °C and based on current technology and utility and capital prices. The profitability of an exhaust heat recovery project is closely dependent on the size of the exhaust heat exchanger and its face velocity. Results from the model indicate that 4 m/s face velocity is a good trade-off between reducing fouling while maintaining an acceptable pressure drop. IRR analysis suggests the exhaust heat exchanger should contain only a few rows of tube (4 – 6 rows) whereas NPV analysis favours a larger exhaust heat exchanger with 12 -14 rows. The spreadsheet tool has flexibility to be applied to any milk powder plant to optimise the economics of an exhaust heat recovery system. Site selection for the first exhaust heat recovery projects is important to determine the sites with the greatest economic benefit.

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