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Innovative Hybrid Heat Pump for Dryer Process Integration

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This study aims to simulate and optimise a hybrid compression-absorption heat pump process for convective dryers considering Pinch design principles. With a greening electricity grid, heat pumps represent an effective technology to reduce process heat emissions. As a result, numerous types of heat pumps integrated with convective dryers have been reported in the literature, but no study was found to use a hybrid heat pump. To simplify the design and optimisation, Process Integration principles for compressors and expanders from literature are synthesised into a Pinch design method for heat pumps. A milk spray dryer case study is analysed. Simulation results using Petro-Sim™ show that the optimally design hybrid heat pump system can reduce dryer energy demand by 47.3 % and total emissions by 42.4 % (assuming a low carbon electricity grid) while achieving a gross Coefficient of Performance of 4.53. Future work will look at optimising the selection and composition of working fluid for the hybrid heat pump system as well as investigating the economics of its implementation in industry.

1. Introduction

Convective dryers are an energy intensive process unit operation required by several industries, e.g. pulp and paper, wood, food and beverage, and pharmaceutical. In most instances, fresh air is drawn into the system and heated to a set temperature. The hot dry air enters the dryer and removes moisture from the liquid or solid feed such that the exhaust air is humid and warm. Separation operations then remove entrained particulates from the exhaust air. The dryer operation may include multi-staged drying operations to provide a longer residence time to extract sufficient water from the core of the product while also cooling the product. Within the dryer system boundary, some exhaust air may be recycled to further increase dryer energy efficiency by reaching a lower exhaust temperature and higher absolute humidity.

With the prospect of a renewable electricity future, heat pumps are emerging as a key technology to enable a step reduction in process heat emissions and associated fossil fuel consumption. The idea of using heat pumps to integrate convective dryers has been investigated in numerous studies (Minea, 2013). Heat pump cycles considered for dryers include: vapour compression and transcritical cycles (Wang and Cleland, 2011), open absorption cycles (Anderson and Westerlund, 2014), closed absorption cycles (Tran et al., 2016), and solar assisted cycles (Suleman et al., 2014). Wang and Cleland (2011) studied a milk spray dryer finding a transcritical R-134a cycle achieved the highest Coefficient of Performance (COP).

One emerging heat pump technology is a hybrid vapour compression-absorption heat pump. In this cycle, elements of the vapour compression cycle and absorption cycle are combined. The cycle uses a binary fluid, e.g. ammonia-water. Using a binary fluid results in significant “temperature glide” for evaporator and condenser heat transfer operations. As a result working fluid composition may be selected to achieve different temperature glide profiles that match process heat demand profiles. For this cycle, the evaporator outlet is a vapour-liquid mixture, requiring a separator connected to a compressor and a pump to raise the pressure of the working fluid. The application of hybrid vapour compression-absorption heat pump for dryer integration represents a gap in the literature.

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Early in the development of Pinch Analysis, Townsend and Linnhoff (1983) introduced the idea of the appropriate placement of heat pumps, which states that heat from the below the Pinch should be upgraded to satisfy demands above the Pinch (Klemeš, 2013). This principle holds true for all types of heat pumps including in applications, including open cycle systems (Walmsley et al., 2016). For heat pump design, it is useful to apply appropriate placement principles for individual components. Through exergy analysis, Fu and Gundersen (2015) derived rules for the appropriate placement of compression and expansion operations. Consequently, close matching of heat load profiles is desirable from an exergy transfer viewpoint to minimise exergy destruction and thereby aim to reduce the work of compression and/or high-quality heat inputs (Fu and Gundersen, 2016). These principles can also be applied to the Pinch design of the hybrid vapour compression-absorption heat pump for dryers.
This paper aims to simulate and optimise a hybrid compression-absorption heat pump process for convective dryers considering Pinch design principles. The process simulation is modelled using Petro-Sim^{TM} (KBC, 2016). A milk spray dryer case study demonstrates the application of a hybrid heat pump.

2. Dryer process integration schemes

Four methods for dryer process integration are illustrated in Figure 1. Option A is direct heat recovery of the exhaust air to the inlet air (or another cold process stream, if available). A barrier to implementing this method is the distance between the exhaust air stream and the fresh air intake, which for a milk spray dryer it's desirable to separate the inlet and exhaust ducts. In such cases, a liquid coupled loop heat exchanger system may be installed to allow for exhaust-inlet separation and simpler retrofit (Option B). Options A and B can recover similar levels of heat, about 15% of the air heater duty for milk spray dryers (Walmsley et al., 2015), but are limited by the exhaust temperature, which drives the Pinch Temperature. Option C adds a heat pump to the system. However, the capital cost for the system greatly increases as the number of heat exchangers increases to four as well as a compressor. Option D, although less thermodynamically efficient, synthesises the liquid coupled loop system with the heat pump to combine benefits and reduce capital cost. This solution follows the appropriate placement of a heat pump principle if the dryer exhaust and inlet air are considered as separate zones. This study focuses on Option D.

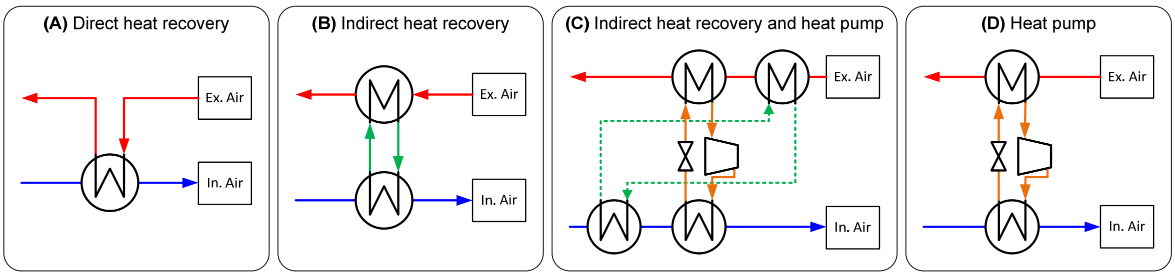

Figure 1: Typical dryer exhaust-to-inlet air flow process integration schemes.

3. Methods

3.1 Pinch principles for heat pump cycle design for a dryer

Appropriate placement principles for heat pump components may be synthesised into a Pinch design method for a hybrid heat pump (Figure 2). Fu and Gundersen (2015) show the appropriate placement of a compressor starts at the Pinch providing heat above the Pinch. An expander is appropriately placed starting at the Pinch and providing cooling below the Pinch. These principles are applied to the design of a hybrid compression-absorption heat pump as shown in Figure 2. Since the exhaust and inlet air streams are treated as two zones, the shifted exhaust temperature drives the hot Pinch and the cold inlet air determines the cold Pinch. Accordingly, the inlet of the compressor/pump is ideally $T_{ExAir} - \Delta T_{min}$ and the inlet of the expansion valve is $T_{InAir} + \Delta T_{min}$. There is the further constraint that the outlet of the condenser is 100 % liquid (saturated or sub-cooled). The heat profiles of the working fluid in the evaporator and condenser are affected by the composition of the fluid.

3.2 Hybrid vapour compression-absorption heat pump simulation model

A hybrid vapour compression-absorption heat pump simulation has been undertaken in Petro-Sim^{TM} as shown in Figure 3. The binary working fluid is ammonia-water. Fluid properties are based on the Peng-Robinson formulation in combination with the Lee-Kesler equation of state as a standard package in PetroSim.

Very low-quality vapour (~5 %) ammonia-water fluid enters the evaporator. As heat is transferred from the exhaust air (ExAir), significant temperature glide occurs generating a vapour phase rich in ammonia and a liquid phase rich in water that exits the evaporator. The evaporator outlet temperature is $T_{ExAir} - \Delta T_{min}$. The vapour and liquid phases are then separated and appropriately supplied to the compressor and pump. After the mixer, high quality (~75 %) saturated vapour condenses to saturated liquid ammonia-water, once again with significant temperature glide. At this point, the model uses a recycle operation to break the cycle so that the conditions of S-010 may be specified, i.e. saturated liquid and selected temperature. Mass flow rate of the working fluid automatically adjusts to achieve a target ΔT_{min} for the condenser. Saturated liquid then sub-cools to $T_{InAir} + \Delta T_{min}$. The fluid completes the cycle by passing through the expansion valve returning to the evaporator.

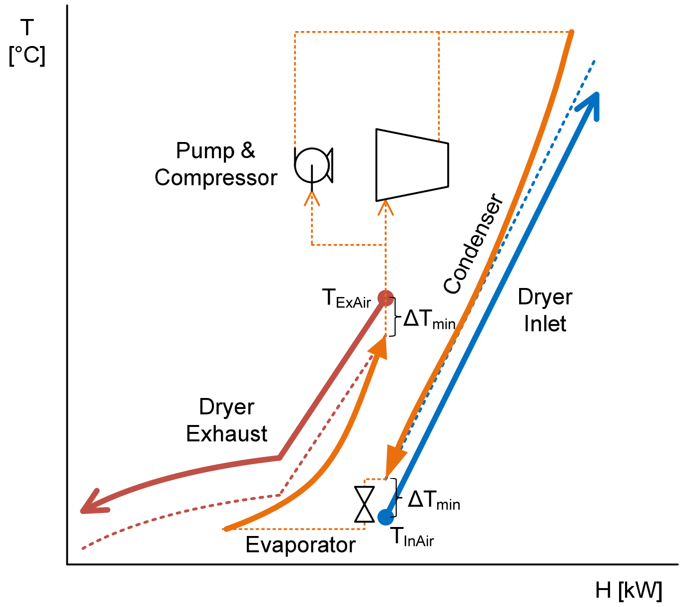

Figure 2: Pinch design of a hybrid heat pump cycle and its components integrated with a dryer exhaust and inlet air streams.

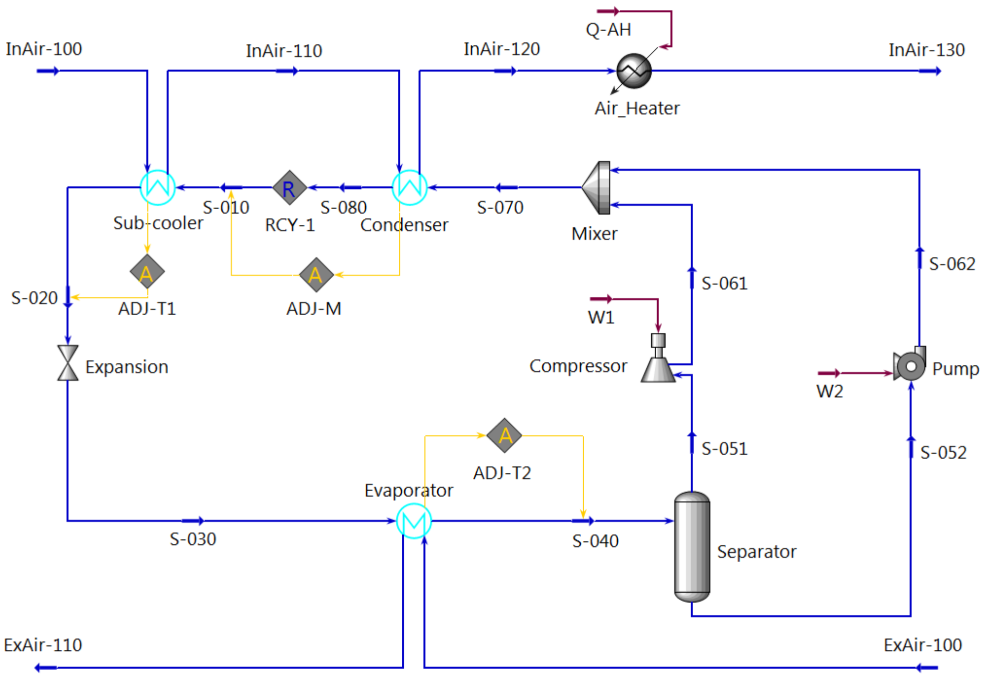

Figure 3: A Simulation model of a hybrid vapour compression-absorption heat pump in Petro-Sim.

The simulation requires four specified inputs to solve: (1) binary fluid composition, (2) heat exchanger approach temperature, ΔT_{min}, (3) the saturation temperature (or pressure) at the outlet of the condenser, and (4) the evaporator inlet temperature (or pressure). For this study, ΔT_{min} is set at 15 °C for all heat exchangers and the binary fluid is 80 mol% ammonia – 20 mol % water. The pump has an estimated 75% isentropic efficiency and the compressor has an efficiency based on the required compression ratio (Wang and Cleland, 2011) using

$$\eta_{comp} = \eta_{motor}\eta_{isen} = \eta_{motor}\left(0.65 + 0.015r - 0.0015r^2\right), \quad \text{where} \quad \eta_{motor} = 0.98, \quad r = \frac{P_o}{P_i} \tag{1}$$

3.3 Energy and emissions performance coefficients

A number of ratios are defined to characterise heat pump performance. The gross Coefficient of Performance, COP_{gross}, for the dryer heat pump, is

$$COP_{gross} = \frac{Q_{HP}}{W}, \quad \text{where} \quad Q_{HP} = Q_{Sub} + Q_{Cond} \tag{2}$$

However, it's important to recognise that not all of the heat delivered by the heat pump, Q_{HP}, required upgrading. Some of the heat, $Q_{HR,tar}$, could have alternately been recovered using a liquid coupled loop system. As a result, a COP_{net} based on the required heat pump contribution is

$$COP_{net} = \frac{Q_{HP} - Q_{HR,tar}}{W} \tag{3}$$

The proportion of process heat demand, Q_{demand}, satisfied by the heat pump system, α_{HP}, is

$$\alpha_{HP} = \frac{Q_{HP}}{Q_{demand}} = \frac{1}{1 + Q_{AH}/Q_{HP}}, \quad \text{where} \quad Q_{demand} = Q_{HP} + Q_{AH} \tag{4}$$

A detailed analysis of heat pump integration impact on emissions is also undertaken using average Emission Factors (EF). For this study, the Emissions Reduction ratio (ER), which is the ratio of emissions reduction per unit of dryer heat demand, is

$$ER = \frac{Q_{HP}EF_{heat} - W \cdot GEF}{Q_{demand}EF_{heat}} = \alpha_{HP}\left(1 - \frac{1}{COP_{gross}}\left(\frac{GEF}{EF_{heat}}\right)\right), \quad \text{where} \quad EF_{heat} = \frac{EF_{fuel}}{\eta_{boiler}} \tag{5}$$

The study assumes as a base case that steam from a natural gas boiler with an 85 % efficiency heats inlet dryer air to 200 °C from an average of 15 °C. A typical EF_{fuel} for natural gas is 53.3 $kg_{CO2\text{-}e}/kJ_f$ (Ministry for the Environment, 2007). The EF_{heat} for process heat is 62.7 $kg_{CO2\text{-}e}$/MJ after accounting for boiler efficiency.
Heat pumps replace process heat from fossil fuel for process heat from electricity at the ratio of the COP_{gross}. Current global aspirations are to move towards renewable, low carbon national and regional electricity grids. As a representative renewable electricity grid, New Zealand has 82.6% renewable generation and a Grid Emissions Factor (GEF) of 29.5 $kg_{CO2\text{-}e}$/MJ in 2016 (MBIE, 2016).

4. Milk spray dryer case study

A milk spray dryer case study provides the contexts for demonstrating the application of a hybrid vapour compression-absorption heat pump. The main dryer inlet air enters at 15 °C and a humidity of 5 g/kg_{DA}. The heat pump in combination with a steam heater then raises its temperature to 200 °C. The exhaust air, which includes air from the spray dryer and associated fluidised beds, exits at 75 °C and 47 g/kg_{DA}, which is a dew point temperature of 39.5 °C. The mass flow rate ratio of total exhaust air to dryer inlet air is 1.25 kg/kg.

5. Results and discussion

5.1 Effect of condenser and evaporator temperature selection on performance

Multiple combinations of condenser saturation temperature (40 – 80 °C) and evaporator inlet temperature (15 – 25 °C) have been simulated using the hybrid heat pump model as shown in Figure 4. These results apply a ΔT_{min} of 15 °C for all heat exchangers and a binary fluid with 80 mol% ammonia – 20 mol% water. COP_{net} (Figure 4B) shows a peak value for the selected evaporator inlet temperatures when the condenser saturation temperature is about 55 °C. The highest COP_{net} is achieved for an evaporator inlet temperature of 25 °C; however, this is also for the lowest α_{HP}, which is equivalent to the amount of steam utility reduction.

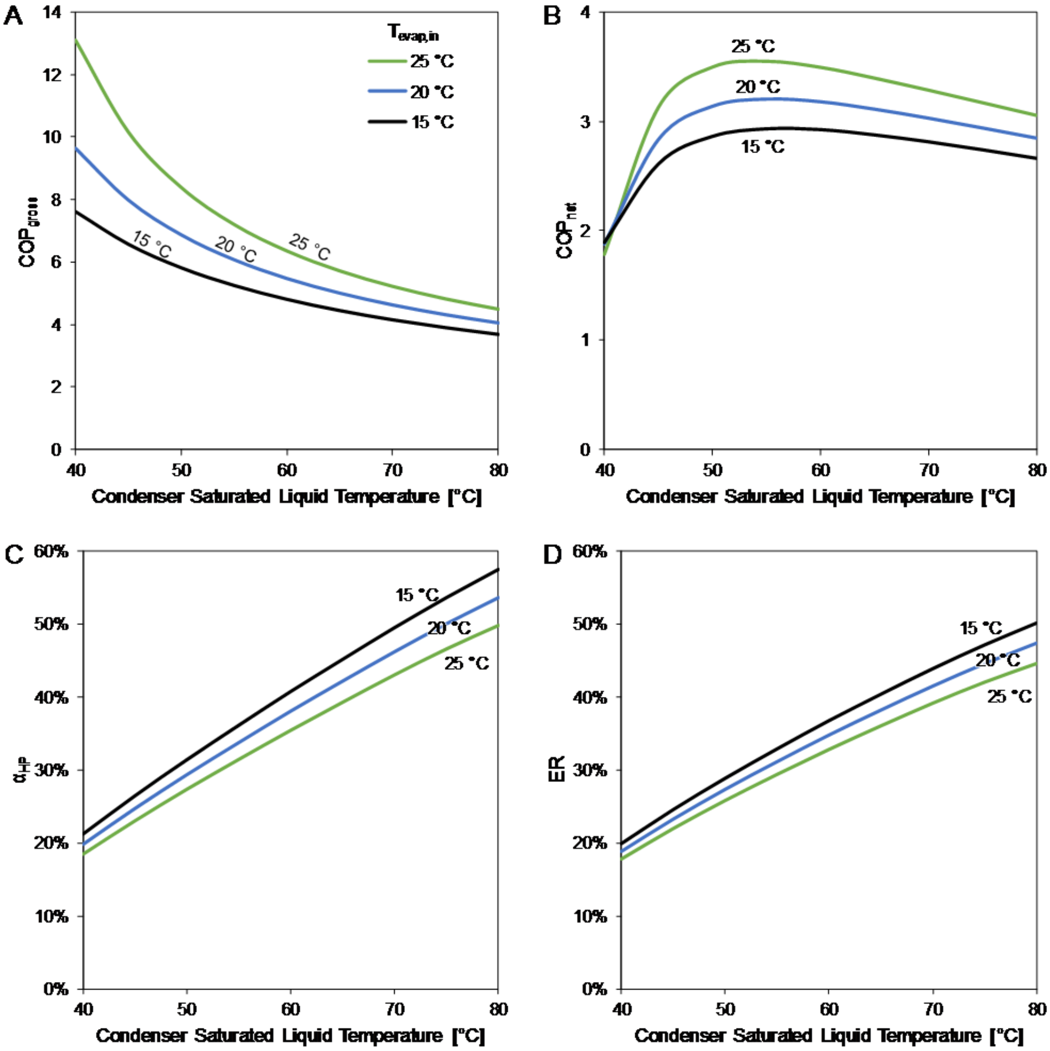

Figure 4: Effect of condenser and evaporator temperature specifications on performance.

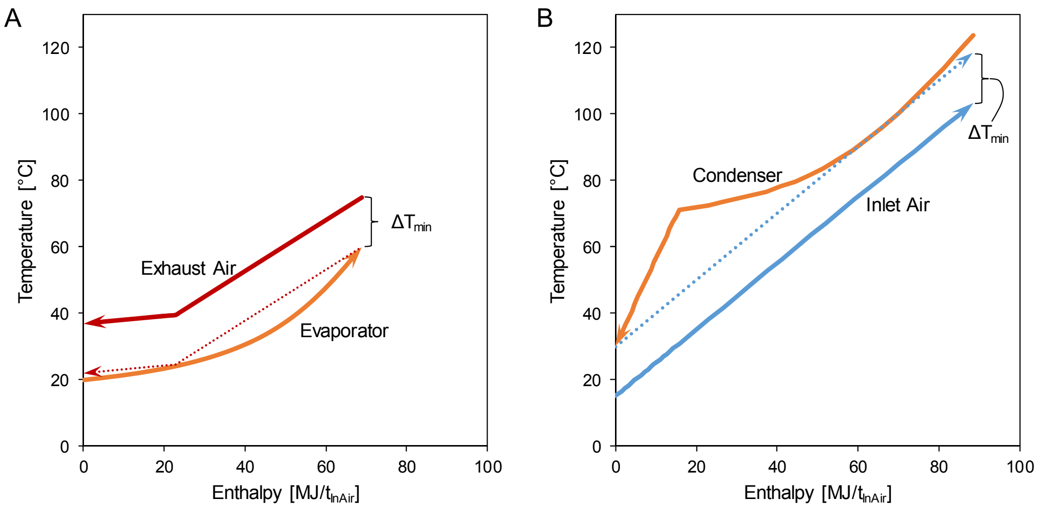

Figure 5: Optimised heat load profiles for a binary fluid with 80 mol% ammonia – 20 mol% water.

5.2 Maximum energy and emission reduction through optimal temperature selection

Energy and emission reductions for a hybrid heat pump dryer may be maximised through optimal selection of condenser saturation temperature, evaporator inlet temperature, as well as evaporator outlet temperature. In the previous simulations, the evaporator outlet temperature was fixed at 60 °C, i.e. $T_{ExAir} - \Delta T_{min}$, following the Pinch design principle. The optimisation problem set a target COP_{net} of 3.0. This constraint ensured a minimum performance level for the objective of maximising energy and emission reductions.

In the Petro-Sim optimisation, the condenser saturation temperature converges to 71.2 °C and the evaporator inlet temperature to 19.4 °C. Lifting the constraint for evaporator outlet temperature also confirmed that 60.0 °C is indeed the optimal temperature for the evaporator outlet given a ΔT_{min} of 15 °C. The heat load profiles for the evaporator (A) and condenser (B) are presented in Figure 5. Using ammonia-water as the working fluid allows excellent matching between heat load profiles, especially in the evaporator, thus minimising exergy destruction. For the optimised design, the compression ratio is 4.07 with a compressor efficiency of 67.3 %. The heat pump substitutes 47.3 % of the air heat duty with 42.4 % emissions reductions.

6. Conclusions

This study simulated a hybrid vapour compression-absorption heat pump using a milk spray dryer as the case study. Pinch design principles for a heat pump, including its key components, are synthesised from literature. Results confirm the validity of these Pinch design principles. With an optimal design for the case study, the hybrid heat pump decreased utility heater load by 47.3 % and total emissions by 42.4 %. Future work will look at optimising the selection and composition of working fluid for the hybrid heat pump system as well as investigating the economics of its implementation in industry.

Acknowledgments

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