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OPTIMIZATION OF A TRANS- CRITICAL HEAT PUMP CYCLE USING A MIXTURE OF PROPANE AND BUTANE INTEGRATED WITH AN INDUSTRIAL DRYER

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1. ABSTRACT

An integrated heat pump & dryer system is proposed. Moist air exiting the dryer is used as a heat source for the heat pump, but also to pre-heat ambient air. The heat pump performance is optimized by considering a trans- critical cycle with different mixtures of propane and butane. The mixture composition of 12.5% propane and 87.5% butane yields a CoP of 4.05 (vs. 3.96 for pure butane). The optimal performance can be traced back to better glide matching in the evaporator and reduced irreversibility generation in the valve.

2. INTRODUCTION

Within the European Union, 20% of the greenhouse gas emissions is caused by the industrial sector. Two-thirds of these emissions are the direct consequence of generating process heat through the combustion of hydrocarbons (de Boer, et al. 2020). By adopting electric-driven heat pumps, heating processes can be decarbonized efficiently as they offer the possibility to upgrade on-site waste heat to process heat.

Drying processes in the food- and paper industry are ideal to be decarbonized using heat pumps as the required temperature is typically in the range of 70 °C to 200 °C. However, heat pumps currently on the market do not reach temperatures over 150 °C, yet. Therefore, new cycles will have to be developed for the temperature range 150 °C – 200 °C. Such cycles should have a large coefficient of performance (CoP) and use as much available energy as possible. To reach optimal performance, the temperature glide on the process stream and the refrigerant should be matched in order to minimize exergy losses associated with stream-to-stream heat transfer. One option is to consider trans-critical cycles (Zhou, Pecnik and Peeters 2024). However, such cycles do not enable glide-matching in the evaporator. The latter can only be achieved by using a zeotropic mixture as the refrigerant.

In this work, we propose a cycle that utilizes both strategies: a trans-critical cycle that uses a mixture of butane and propane as a refrigerant. Both propane and butane have a low global warming potential and ozone depletion potential. Furthermore, such mixtures are widely available and may be considered to be reasonably safe. The mixture composition is optimized to generate hot air for a drying process up to 180 °C. Combining the aforementioned strategies has been suggested before to optimize the performance of trans-critical power cycles (Rodríguez-deArriba, et al. 2022)

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3. METHDOLOGY

The heat pump- dryer integrated system studied here is shown in figure 1. In this system, the residual heat from the dryer (moist air) is used as a heat source for the evaporator and the air pre-heater. Air at ambient conditions and at a temperature of 10 °C (A1) is pre-heated to 40 °C (A2) using the residual heat of the air exiting the evaporator (A5). The air is then heated to 180 °C in the condenser (A3), using the heat delivered by the refrigerant between states R3 and R2. Moist air exits the dryer at 80 °C and at a relative humidity of 0.4. The moist air is used to super-heat the refrigerant from state R5 (after the valve) to R4 (just before the compressor) as indicated. Thus, the temperature of the refrigerant will always be below 80 °C.

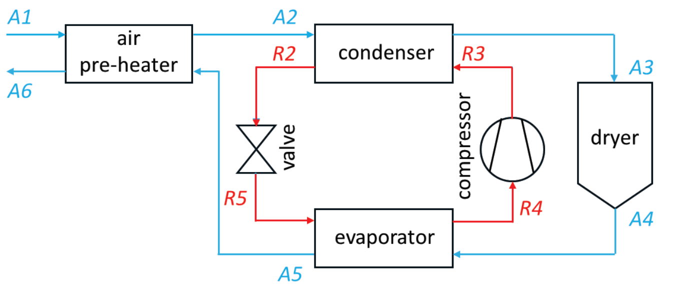

Figure 1: The heat pump- dryer integrated system showing the components considered in black, as well as the labels for the different states of air in blue and the states of the refrigerant in red.

For all components, steady state mass- and thermal energy balances are solved using an in-house python code (Zhou, Pecnik and Peeters 2024). All thermodynamic properties of the propane-butane mixture are evaluated using the GERG-2008 equation of state (Kunz and Wagner 2012). Apart from the conditions already mentioned, the following conditions apply: 1) In the evaporator, the refrigerant mixture is superheated to 7.5 °C above the saturation temperature to avoid wet compression. 2) The minimum temperature difference at any pinch point in the evaporator and condenser is set to a minimum of 5 °C. 3) The condenser is considered to be balanced. Finally, 4) The isentropic efficiency of the compressor is set to 0.7.

Using these conditions, different compositions of the propane-butane mixture are considered ranging from pure propane to pure butane. For each composition, the pressure ratio of the compressor is optimised such that the temperature of the refrigerant is sufficiently high that air is heated to 180 °C (refrigerant temperature at least 185 °C) and that the pinch-point requirement is not violated. For each composition, the coefficient of performance, and the rate of exergy destruction due to internal irreversibilities per component are recorded.

4. RESULTS

Figure 2 shows the result of the optimization procedure for the different compositions of the propane-butane mixture. The optimal CoP is found to be 4.05 for a composition of 87.5 % butane and 12.5 % propane. This optimal value is much higher than the CoP for pure propane (3.54) and moderately higher than for pure butane (3.96). Furthermore, the rate of exergy destruction is minimal for the same mixture composition.

Three cycles– pure propane, pure butane, and the optimal mixture composition – are compared in figure 3. The compression process-line for the butane cycle lies very close to the multiphase region. In the cycle with

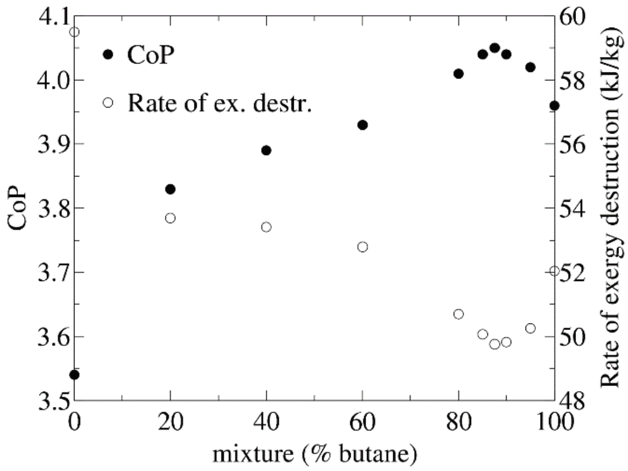

Figure 3: CoP and rate of exergy destruction vs. mixture composition. A X % of butane means 100 – X % of propane.

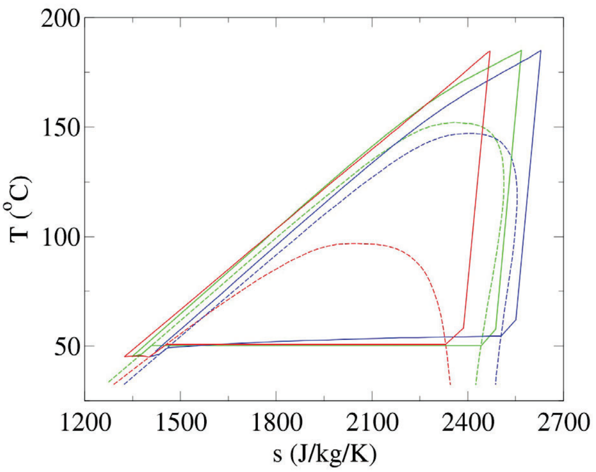

Figure 3: three different cycles for pure propane (red), pure butane (green) and the optimal mixture composition (blue).

the mixture, the process-line lies further away. The latter is likely the result of propane being a wet fluid. Furthermore, it is clear that the evaporator process line with the mixture has a small glide; this glide matches much better with the glide of the moist air, than it does in the pure fluid cycles. Two more important observations can be made: 1) the pressure ratio is lowest for the pure propane cycle and highest for the butane cycle and 2) the entropy difference across the valve is largest in the propane cycle. From a second law viewpoint, the optimal mixture composition combines the best of two worlds. It has the lowest exergy destruction in the evaporator, and much less irreversibility is generated in the valve compared to the propane cycle, which explains the optimal performance discussed before.

5. CONCLUSIONS

Using a mixture of propane and butane in a trans-critical cycle (aimed at heating air to 180 ^{o}C) yields an enhanced performance compared to pure propane or butane cycles when utilizing the heat from the moist air that exits the dryer. The enhanced performance stems from the fact that for the optimal mixture composition, the glide of the moist air and the refrigerant match better. Furthermore, much less irreversibility is generated in the valve. The methods that were used to generate these results can be extended to different mixtures to find other optimal mixtures.

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