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Deriving guidelines for the design of plate evaporators in heat pumps using zeotropic mixtures

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ABSTRACT

This paper presents a derivation of design guidelines for plate heat exchangers used for evaporation of zeotropic mixtures in heat pumps. A mapping of combined heat exchanger and cycle calculations for different combinations of geometrical parameters and working fluids allowed estimating the trade-off between heat transfer area and pressure drops on the thermodynamic and economic performance indicators of the cycle. Compressor running costs constituted the largest cost share, and increased due to a steep decrease of the heat pump coefficient of performance at high refrigerant pressure drops. It was found that the pressure drop limit leading to infeasible designs was dependent on the working fluid, thereby making it impossible to define a guideline based on maximum allowable pressure drops. It was found that economically feasible designs could be obtained by correlating the vapour Reynolds number and the Bond number at the evaporator inlet as $\mathrm{Re}_V^{-0.42}\mathrm{Bd}^{0.26} \approx 0.040$. The use of the proposed guideline was illustrated for the mixture Propane/Iso-Pentane (0.5/0.5), leading to evaporator designs with net present values deviating maximum −4.4% from the best value found in the mapping. The presented methodology can be applied in different scenarios to develop similar guidelines, thereby decreasing the cost of combined cycle and component optimizations.

1. Introduction

Zeotropic mixtures are blends of two or more components, with different mass fractions of the liquid and vapour phases at thermodynamic phase equilibrium. Therefore, the temperature at bubble and dew points differ at any saturation pressure and the mixture undergoes a temperature glide during phase change. The use of zeotropic mixtures as working fluids for thermodynamic cycles offers a possibility of optimizing the cycle efficiency by reducing the thermodynamic irreversibility in the heat exchangers (HEXs). Due to non-isothermal evaporation and condensation, the exergy destruction in the HEXs can be reduced by matching the working fluid temperature glide with the heat source and heat sink temperature profiles.

Zühlsdorf et al. [1–3] demonstrated the advantage of using zeotropic mixtures in heat pumps for different applications. A good glide match between the evaporating fluid and the heat source resulted in a beneficial influence on the cycle thermodynamic performance and better improvements were obtained for larger heat source temperature glides [2]. The improvement of using mixtures in a booster heat pump for a district heating system was estimated equal to up 30% compared to pure working fluids. A larger overall improvement up to 40% was achieved for a reduced degree of required superheat imposed in the case of mixtures [3].

One drawback of using zeotropic mixtures is the degradation of the heat transfer coefficient compared to pure fluids, which was observed during both evaporation and condensation in different experimental campaigns, as reported in Refs. [4,5]. In the case of evaporation, several reasons contribute to the heat transfer degradation: (i) an earlier suppression of the nucleate boiling contribution due to an additional mass diffusion resistance created by the more readily evaporation of the more volatile component [6,7]; (ii) large variation of the refrigerant physical properties during evaporation, due to variable compositions of liquid and vapour phases, which, according to Jung et al. [8,9], accounts for the 80% of the total heat transfer degradation; (iii) worse transport properties of mixtures compared to pure fluids [5]. A number of

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studies quantified the heat transfer degradation differently: Ross et al. [6] observed a reduction of up to 50% compared to pure fluids, Jung et al. [8,9] reported varying reduction rates between 19% and 36% depending on the mixture composition, while Torikoshi and Ebisu [10] calculated a degradation of 20% and 30% compared to the heat transfer coefficient estimated by the ideal mixing rule. It is therefore of paramount importance to optimize the design of the heat transfer equipment when zeotropic mixtures are employed, in order to avoid investing in higher heat transfer areas for the heat exchangers.

Plate Heat Exchangers (PHEs) offer a modular and flexible solution for such applications, since it is possible to achieve high heat transfer coefficients within a compact design due to the flow turbulence generated by the characteristic plate corrugation patterns. PHEs are comprised of thin parallel plates stacked together in order to form channels for fluid flow, which can also be arranged in a counter-current manner for achieving a temperature glide match between the mixture and the secondary fluid. Gasketed-type PHEs consist of plates sealed by gaskets and held together by a frame. For higher operating temperature and pressure, the plates can be sealed together by brazing. At the current state-of-the-art, the operating conditions of gasketed-type PHEs are limited to 20.4 bar and 150 °C, whilst brazed heat exchangers can be operated up to 40 bar [11,12], thereby offering a reasonable range of operation at typical heat pump working conditions.

When designing heat exchangers for a given application, different criteria can be adopted to select the geometrical configuration. The pressure drop of one or both fluids can be limited to a maximum allowable value [11,12], and the heat transfer area can be minimized for a full utilization of the available pressure loss, as applied in Ref. [13]. For single phase HEXs, such pressure drop limitations could also be translated into maximum gas and liquid phase velocities at the inlet, and typical design values can be found in literature for a number of heat exchanger configurations [12]. These values are often based on heuristics from manufacturers and the extension to other types of applications (e.g. zeotropic mixtures and/or phase change) is not trivial.

Following other design approaches, the heat exchanger can be optimized by carrying out a cost minimization problem without a maximum pressure drop limitation, and evaluating the trade-off between heat transfer area and pressure drops. Different previous studies have approached the problem by considering solely the cost related to the heat exchanger, namely the investment cost and the pumping and compression costs related to the two streams, for a general heat exchanger configuration [14,15], for shell and tube heat exchangers [16] and for plate heat exchangers [17,18]. However, the economic analysis lacked assessment of the impact of the heat exchanger pressure drops on the other components, as well as on the overall cycle thermodynamic performance.

In literature a number of studies can be found on simultaneous optimization of plate heat exchangers used as evaporators and/or condensers and thermodynamic cycle design, mostly focusing on low temperature applications and pure fluids. Some of the works are related to the assessment of the impact of some specific cycle parameters on the PHE design [19,20], whilst other studies performed combined cycle-PHE optimization procedures with the aim of maximizing the cycle efficiency [21], and by including also an economic analysis [22,23]. The pressure drops were mostly considered as pumping cost on the heat source/sink side, and none of the studies assessed the impact of the working fluid pressure drops on the outlet condition of the evaporator. Moreover, a complete and combined component-cycle optimization comes at a demanding computational cost, especially during the preliminary design phase, when many different working fluids are usually compared and ranked.

The study presented in this paper addresses the following aspects: (i) It presents a methodology for deriving design guidelines for plate heat exchangers integrated in a thermodynamic cycle, namely a heat pump. (ii) The methodology is based on assessing the impact of both plate heat exchanger size and pressure drops on the thermodynamic and economic performance of the heat pump; the pressure losses are not only included as pumping cost of the heat source side, but also imply a modification of the thermodynamic state points of the cycle at the evaporator outlet, which accordingly affects the heat pump design, investment and operating cost. (iii) It utilizes the aforementioned methodology to derive design guidelines for PHE evaporator design in heat pumps using zeotropic mixtures as working fluids. The obtained results are intended for employment in practical engineering during the process of component selection for similar applications, hence avoiding the cost of combined cycle and component analysis.

The methodology is based on complementing a vapour compression heat pump sizing model together with a detailed numerical model of the evaporator, accounting for the variation of the heat transfer coefficient and fluid properties during the evaporation process and estimating the impact of heat transfer area and pressure drops on the cycle thermodynamic and economic performance indicators. The methodology was applied to the case of evaporator design for a heat pump, and eight different working fluids were selected based on a previous study [1], which demonstrated the thermodynamic and economic feasibility of using zeotropic mixtures in heat pumps for waste heat recovery in a spray drying facility.

2. Methods

The methodology adopted in the present study is based on a parametric analysis on the main design parameters of a plate heat exchanger to assess the impact of the different design configurations on the thermodynamic and economic performance indicators of a thermodynamic cycle, namely a heat pump. Fig. 1 shows the schematic of the work flow of the methodology. Two different models were built and integrated in the Matlab environment [24], i.e. a cycle simulation model for a heat pump, explained in details in Section 2.3, and a detailed PHE model, presented in Section 2.4. After the working fluid selection process, explained in Section 2.2, the preliminary sizing of the heat pump was done and the design parameters were calculated, i.e. desired heat exchanger capacity, mass flow rates, pressures and temperatures. The values were subsequently sent to the plate heat exchanger model, which additionally received as inputs the geometrical parameters from which the required heat transfer area and resulting pressure losses were estimated. The outputs were returned to the heat pump model, where the sizing of the cycle was re-evaluated. In this second iteration, the sizing process took into account the resulting heat exchanger size and pressure drops for the economic calculation, as it is briefly described in Section 2.6. The process was repeated for all the combinations of geometrical parameters chosen for the parametric analysis, which is introduced in Section 2.1. Moreover, the same process was repeated for all the eight working fluids considered in the case study, by considering the same combinations of PHE design parameters and calculating the Coefficient of Performance (COP) and Net Present Value (NPV). As shown in Fig. 1, all the data points were collected and used as basis for deriving a general design guideline, valid for all the working fluids and the boundary conditions of the present case study. The aim was to correlate the point with optimal economic performances to the PHE design parameters. In order to generalize the results, non-dimensional parameters were employed as explained in Section 2.8.