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ENHANCED TECHNICAL AND ECONOMIC WORKING DOMAINS OF INDUSTRIAL HEAT PUMPS OPERATED IN SERIES

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ABSTRACT

By operating heat pumps (HPs) in series, it is possible to obtain closer match between working fluid and sink- and source streams, resulting in higher coefficient of performance (COP). For industrial HPs, it was found that serial connection of either two or three units results in an increase in COP and a decrease in net present value (NPV), due to the effects of economy of scale. However, connecting HPs in series may reduce the discharge temperature, which is of particular interest when assessing R717 HPs. Another possibility from serial connection is to mix different types of HP units, in order obtain specific characteristics. The technical and economical working domains were calculated for two serial connections. Both configurations result in an increased working domain for the investigated dual unit serial connections.

1.   INTRODUCTION

Economically viable applications for large heat pumps (HPs) include industrial process optimisation and utility production in district heating networks (Ommen, et al, 2015). For many of such applications, the temperature variation of either source or sink stream may be of a magnitude, where serial connection of HPs may provide an increase in HP coefficient of performance (COP) (Prestmark and Schultz, 1984). On the other hand the economy of scale may suggest that the investment of a single unit is lower than two smaller units, when considering similar heat load. The most profitable solution may further vary with HP parameters such as sink temperature, temperature lift and temperature variation of sink and source streams.

The working domains of several single stage vapour compression HPs (VCHP) were investigated in Ommen, et al (2015). The results were compared to similar results for the hybrid absorption-compression HP (HACHP) in Jensen, et al, (2015). The best available technology typically depends on the performance and investment of the HP systems at the specific layout of the sink/source process streams. Besides the thermodynamic performance of the cycle and working fluid, it is important to consider the application limits of the individual components.

This paper will investigate if the working domains of VCHP may be expanded by connecting the units in series. Four different schemes for serial connection are investigated. Finally the most profitable solution is determined for different sink temperatures, temperature lifts and temperature variations.

2.   METHOD

The enlargement of working domains due to serial operation of units was investigated for two single stage vapour compression HP systems. The individual unit configurations correspond to the previously investigated solutions of single stage vapour compression systems, where improved performance measures such as internal heat exchangers or two stage compression schemes were disregarded. A model of each HP system was implemented in Engineering Equation Solver (F-Chart Software (LLC.), 1992).

The two HP systems (R717HP and R600a) were chosen in order to enhance the working domain of VCHP at high sink outlet temperatures (Ommen, et al, 2015). Of the previously examined VCHP, the two considered systems each contribute with individual benefits and drawbacks. The profitability of R717 systems are typically higher than other natural refrigerants, but the thermodynamic cycle results in very high discharge temperatures which limit the practical applications. The thermodynamic characteristics of R600a results in high COP as well as low pressures and low discharge temperatures, but the economic constraint is decreased

by high investment costs which is explained by a low volumetric heating capacity (large volume flow of refrigerant at compressor suction line for a given heat capacity in the condenser).

The HPs were compared using both economic and technical constraints. The considered technical constraints may be caused by either the thermodynamic cycle or by limitations in the development of suitable components. The economic constraints correspond to a combination of capital investment, fuel cost and operation and maintenance. Both topics are further addressed in the following sections.

A few causes of inefficiencies were neglected, as they are assumed of similar magnitude between the investigated HPs. Examples include pressure drop in pipes, the extent of non-useful superheat and subcooling and compressor heat losses. Only full load steady state operation was considered for the economic analysis.

2.1. Vapour compression heat pump

For many industrial processes heat is transferred by heat transfer fluids, such as oil or water. In this study it was assumed to be pure water, which was pressurized to avoid vaporisation of the secondary working fluid at elevated temperatures. Pinch point temperature differences were used to model heat exchange with both sink and source media. A principle sketch of a vapour compression HP, and a temperature - heat load diagram for an azeotropic working fluid, are presented in Figure 1. In the condenser, the working fluid was assumed sub-cooled until it reaches the pinch temperature difference at the sink entrance. Depending on the slope of temperature variation of the source steam, one of two (or both) locations may be possible for the pinch point of the evaporator. The correct location of the pinch point is handled by the model.
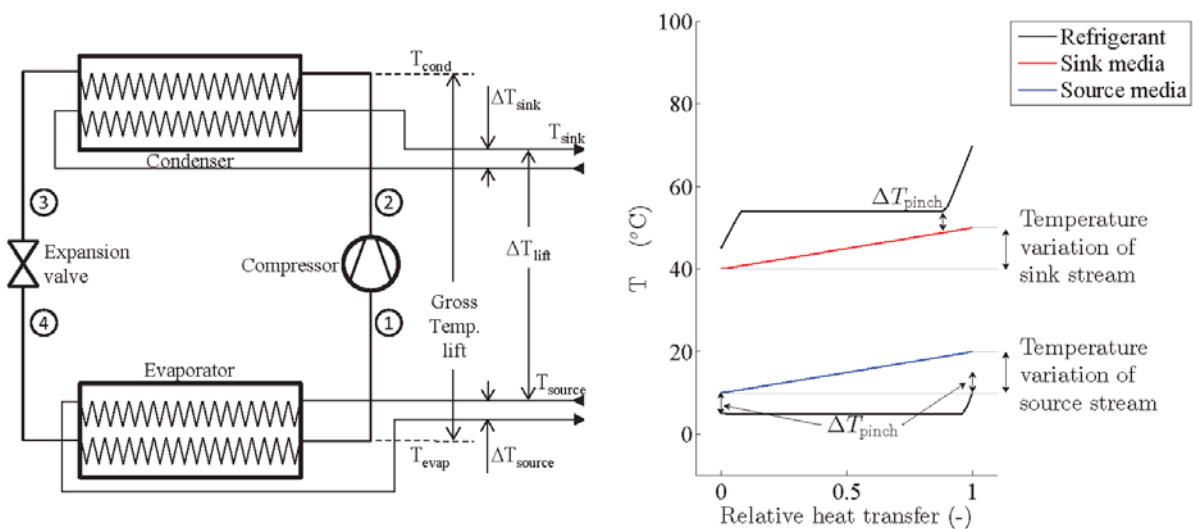

Figure 1: Principle sketch and temperature - heat load diagram of the vapour compression HP

The performance of the HP was calculated using constant efficiencies for compressor and electrical motor, as well as fixed temperature differences in the heat exchangers. The used values are presented in Table 1. The data used for the analysis corresponds to the values used in the two previous studies (Ommen, et al, 2015,Jensen, et al, 2015), where a parametric analysis is performed for key parameters.

Table 1: Fixed input variables for heat pumps

Input variable	Value	Unit
Compressor isentropic efficiency	0.8	-
Compressor volumetric efficiency	0.8	-
Compressor electric motor efficiency	0.95	-
Pinch point temperature difference heat exchangers	5	K
Compressor suction superheat	5	K

Four serial connection schemes are presented in Figure 2. Figure 2a presents the heat load/temperature diagram for two HPs in counter-current configuration considering both sink and source streams, as well as

the refrigerant heat load and temperature profile for each of the HP systems. Figure 2b presents three alternative configurations for the sink and source streams. Counter- and Co-Current configurations are named according to Prestmark and Schultz (1984). The two remaining schemes are variations of the counter-current configuration, where either the evaporators or the condensers are split in parallel connection. The four schemes are further investigated in section 3.

In the case of HP systems operated in series, the optimal configuration depends on the split of heat load between the units. In order to conduct a fair comparison with between various configurations the additional degrees of freedom should be optimised for the system design (Ommen, et al, 2015). The impact of heat load distribution for the individual units is further investigated in section 3.
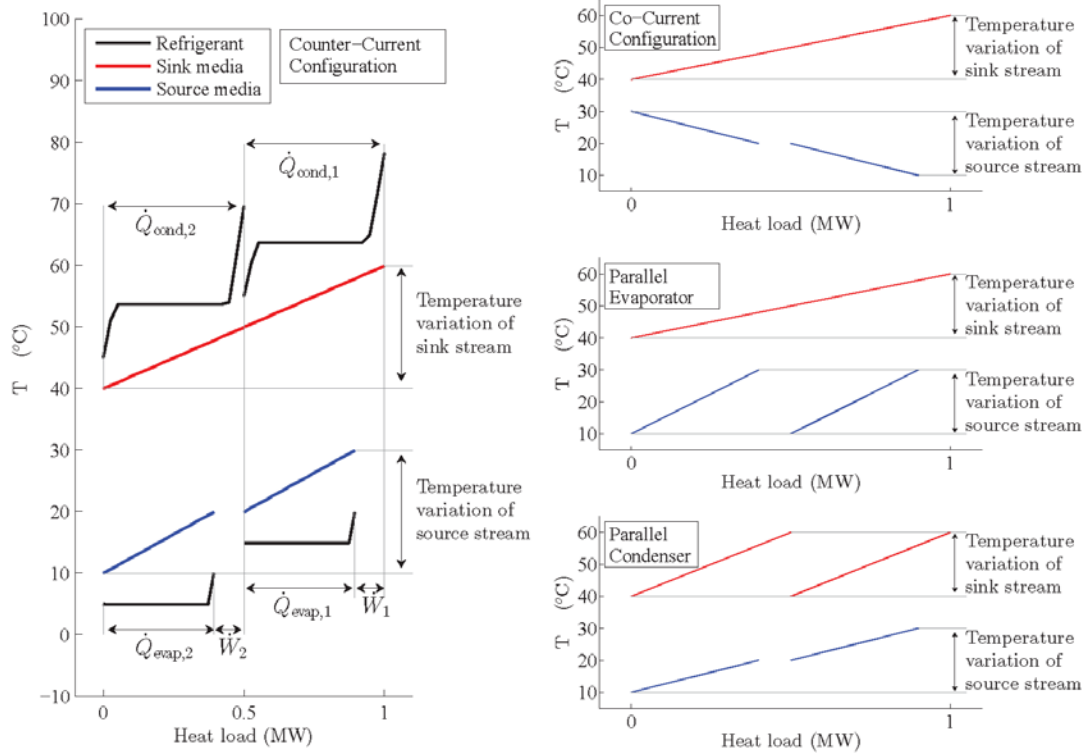

Figure 2: Temperature heat load diagrams of four serially connected HP schemes. (a) Two HPs in counter-current configuration with even split in heat load. (b) Three alternative serial connection schemes.

2.2. Estimation of plate heat exchanger area and pressure drop

Heat exchange processes are important in any HP and a significant part of the physical system, with high influence to the investment and the derived heat cost. Detailed heat transfer correlations for both evaporators and condensers were implemented and used in moving boundary models of the heat exchangers.

In accordance with the applied method of Ommen, et al. (2015), the heat exchange process and required heat exchanger size was calculated for chevron type plate heat exchangers. The correlations used for the analysis are presented in Table 2. The plate dimensions are for a fixed type corresponding to pressure level and working fluid constraints. In this way an increment in heat exchange area will result in increased amount of plates.

Table 2: Applied heat transfer and pressure drop correlations for the evaporator and condenser

Component	Media	Zone	Heat Transfer	Pressure drop
Condenser	H_2O		(Martin, 1996)	(Martin, 1996)
	Refrigerant	vapour only	(Martin, 1996)	(Martin, 1996)
		two phase	(Yan, et al, 1999)	(Yan, et al, 1999)
		liquid only	(Martin, 1996)	(Martin, 1996)
Evaporator	H_2O		(Martin, 1996)	(Martin, 1996)
	Refrigerant	two-phase	(Yan and Lin, 1999)	(Yan and Lin, 1999)
		vapour only	(Martin, 1996)	(Martin, 1996)

2.3. Compressors and operating conditions

In HP applications for industrial processes and district heating, specially designed compressors are used. For most vapour compression HPs, the pressure limit of the high pressure dictates the achievable sink temperatures. For selected fluids (e.g. R717), the condensing temperature (and corresponding pressure) can be lower than that of the sink stream leaving the condenser. This is possible in the case where a high fraction of heat dissipation is from superheated vapour.

The compressor types were identified according to different working fluid properties, flammability and availability. The considered operating limits for the two HP systems are presented in Table 3 (Ommen, et al, 2015).

Table 3: Current operating limits

Working fluid	Pressure limit Bar	Lubrication max. temp ^oC
R600a	28	180
R717-HP	50	180

2.4. Economic evaluation

The economic evaluation of the HPs was based on the economic method presented by Bejan et al. (1996), where individual component costs are used to account for the overall collected system. The method requires detailed cost data for components presented in a process flow diagram.

In order to obtain coherent and comprehensive data for specific components, the aggregation of data required several assumptions. It was assumed that:

- Purchased Equipment Cost (PEC) for an open type compressor was solely dependent on the type and the swept volume of the compressor.
- PEC for an electrical motor with a fixed efficiency was dependent on the shaft power.
- PEC for a heat exchanger was a function of the heat exchange area and pressure limit.
- PEC of an intermediate pressure receiver was a function of volume and pressure limit.
- The PECs of expansion valve and oil separator were neglected.
- Total Capital Investment (TCI) of a component was calculated as 4.16 higher than PEC of the component (Bejan, et al, 1996). This was done to account for additional cost related to new investment at an existing facility. The costs include installation, piping, instrumentation, electrical equipment, engineering and supervision, as well as start-up and working capital etc.
- Electricity and natural gas prices correspond to the market cost for industrial consumers in the year 2012 according to Danish Energy Agency (2013).
- The investment costs of already installed natural gas burners were neglected. This is the case if the HP replaces an existing installation.
- Source heat was assumed readily available as a process stream.

Table 4: Parameters applied in the economic analysis

Parameter	Value	Unit
Heat pump load	1000	kW
Interest rate	7	%
Inflation rate	2	%
Natural gas burner efficiency	0.9	-
Technical lifetime	15	Years
Operating time	3500	Hours pr. year
Gas burner investment cost	0	€
Gas burner maintenance cost	0	€

Purchased equipment cost functions were developed based on prices from intermediate Danish trade businesses and individual manufactures. The cost functions were constructed as proposed by Bejan et al. (1996) where the purchase cost of an equipment item PEC_Y at a size or capacity X_Y can be calculated based on knowledge of the cost PEC_W at a different size or capacity X_W by use of a scaling exponent α. Data for the component cost correlations and references are listed in Ommen et al. (2015) for the investigated HP systems. Cost correlations were estimated to be valid for HP capacities between 100 kW and 2 MW.

When comparing technical solutions the economically best available solution is preferred. Two different profitability criteria were used for the analysis, the (simple) payback period (PBP) and the net present value (NPV) utilising discounted cash flows. The methods for determination of the two factors are explained in Ommen, et al. (2015).

3. RESULTS

In Ommen et al. (2015) it is shown that temperature variation of both heat sink and heat source streams have significant influence on both the economic and technical constraints of VCHPs. In the present study two of the proposed cases with high temperature variations were examined. The two cases are denominated: $\Delta T_{sink}/ \Delta T_{source}$ = 20K/20K and 40K/10K. Temperature variations are presented graphically in Figure 2.

The four schemes for serial connection were compared to the same reference system, containing only one HP. With a higher number of units, both economy and energetic efficiency is altered based on the changed temperature levels as presented in Figure 2a. The results in terms of COP and NPV are presented in Figure 3 for the two temperature variation cases, i.e. the changes of the sink and source streams in the condenser or evaporator, respectively. All systems were calculated for 1000 kW, and with even heat load distribution for serial connected units. For both $\Delta T_{sink}/ \Delta T_{source}$ variations it was found that serial connection of either two or three units result in an increase in the COP and a decrease in NPV, when compared to the reference system with only one HP. The decrease in the NPV is the result of a significant increase in investment cost, which is not fully compensated by the decrease in operation cost. Accordingly, it was found that HP units in serial connection perform best for the case 20K/20K compared to 40K/10K, as the increase in energetic performance is lower for the latter. This may be the case as the change to evaporation temperature is larger with a large variation in source temperature. Additionally, the two configurations 'Counter-current' and 'Co-current' perform similar in both temperature cases, and are favourable both in terms of COP and NPV to the solutions with parallel connection of evaporator or condenser. Based on the results presented in Figure 3, further investigation of economic and technical working domains were limited to include two HPs in counter-current configuration, as this scheme results in lower maximum pressure ratio and consequently lower discharge temperatures compared to the co-current scheme.
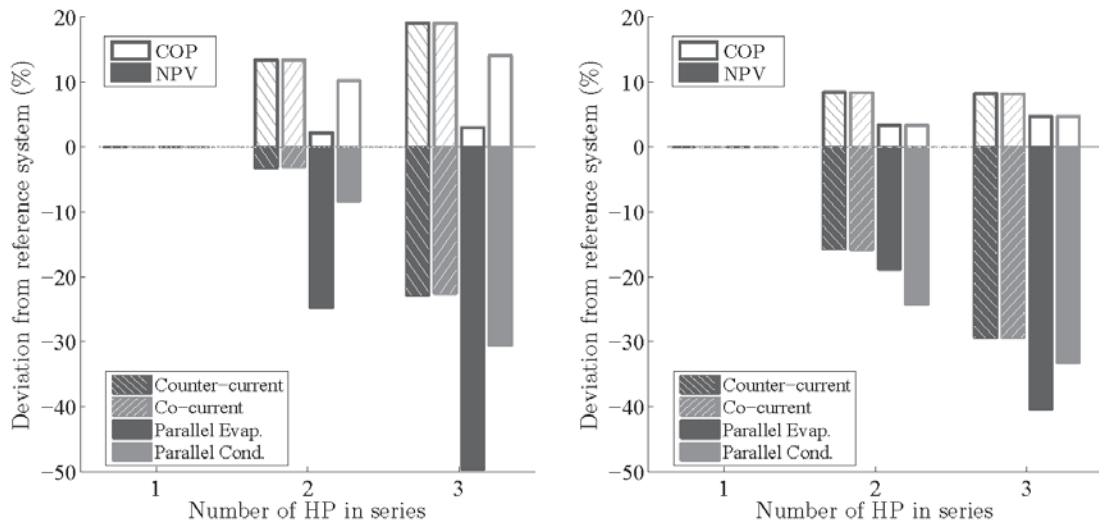

Figure 3: Changes to COP and NPV for four serial connected HP schemes with even heat load for serial connected units. In the considered case, all units were of the same type (R717-HP).
(a) $\Delta T_{sink}/ \Delta T_{source}$ = 20K/20K. (b) $\Delta T_{sink}/ \Delta T_{source}$ = 40K/10K

For the serially connected HPs, the split of heat load between the units is an additional degree of freedom which should be considered. The impact of variation of the load distribution is presented as contours in Figure 4a and Figure 4b for the COP and NPV, respectively. The load distribution for HP_1 is defined as the heat load of HP_1 compared to the combined load (sum of load for HP_1 and HP_2 - 1 MW for the presented results). In Figure 4b curves for technical constraints are presented for the unit with the highest discharge temperature (180^oC), as well as the condenser pressure for the unit with the highest high side pressure. Based

on the slope of constant COP and NPV contours, the heat load distribution has a higher impact to the COP than to the NPV. For both performance criteria it is clear that the temperature lift has a high influence. As NPV is not sensitive to the heat load distribution, other influences to the technical constraints may prove significant. It is seen that an even heat load split allows higher temperature lift of the total installation, compared to the case where one of the units has a significantly higher share of heat load than the other. At a fixed temperature lift the highest condenser pressure may vary by approximately 2 bar. The gain from even heat load split to the case with the lowest condenser pressure is a reduction of approximately 1 bar. As the discharge temperature is found to be a major factor to limitations of working domains in Ommen et al. (2015) the heat load fraction of the configuration utilised for calculation of the working domains was kept at 0.5 (-).
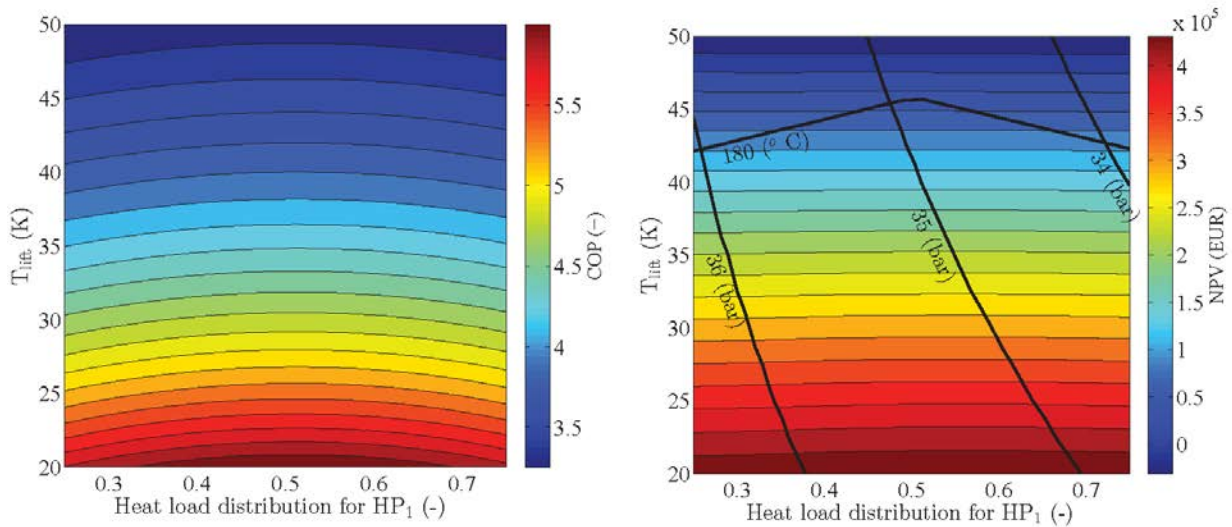
Figure 4: COP and NPV variations with variation of the heat load fraction and temperature lift. Results are calculated for $T_{sink} = 70$ (^{o}C) and $\Delta T_{sink}/ \Delta T_{source} = 20K/20K$.

The enhanced working domains for VCHP are presented in Figure 5. Each individual plot shows the constraints for the serially connected HP units, showing both the technical and the economic restrictions. The economic constraints are presented as green curves (NPV) and turquoise curves for PBP = 8 years. Red curves indicate high discharge temperatures, whereas blue curves show the pressure constraints. Series #1 corresponds to two R717-HP HPs, Series #2 corresponds to R600a for unit 1 and R717-HP for unit 2. For the two plots presenting Series #1 (Figure 5a and Figure 5b) it was found that the working domain is constrained by two technical constraints (maximum allowable pressure and discharge temperature). For both cases the pressure constraint limits the working domain at sink temperatures below 90 ^{o}C, whereas the temperature lift is constrained at approximately 45 K for the 20K/20K case, and 53 K for the 40K/10K case, respectively. For Series #2, the economic NPV constraint is limiting the working domain in terms of high temperature lift. The pressure constraint (limitation in terms of high sink temperatures) of Figure 5c and d corresponds to the technical constraint of R717-HP components of the HP$_2$ unit, which result in sink temperatures of approximately 96 ^{o}C for the 20K/20K case and 107 ^{o}C for the 40K/10K case. The difference in achievable sink temperatures is due to the sink temperature glide for the two cases.

In Figure 6 the working domains of Series #1 and #2 are compared to the best available working domains of the previous study. Figure 6 (a & b) compares the limiting constraints, and in (c & d) the areas are hatched with the most profitable vapour compression technology based on NPV. For both $\Delta T_{sink} / \Delta T_{source}$ variations, the serially connected HPs expand the working domain in areas, which are not possible to operate by other configurations. In parts of the areas where the previous recommendation was installation of an R600a unit, Series #2 replaces the area due to higher profitability.

4. DISCUSSION

For an in depth discussion of the assumptions for working conditions, economic parameters and the applied correlations for heat exchangers and component costs, the reader is referred to Ommen et al. (2015) and Jensen et al. (2015). A possible improvement would be the use of polytropic efficiency for the comparison

of VCHP operated in series with a single VCHP. The differences in terms of NPV and discharge temperatures are expected to be low.

It is important to note, that the negative impact to NPV from increasing the amount of units (in serial connection) corresponds to economy of scale. In the HP model this effect corresponds to the slope of the validated cost correlation. In the case where it is not possible to utilise larger components (due to lack of availability) the NPV should be compared to the case of two or more HPs in parallel. In this case the serial connected HPs may have a lower NPV than the alternative.
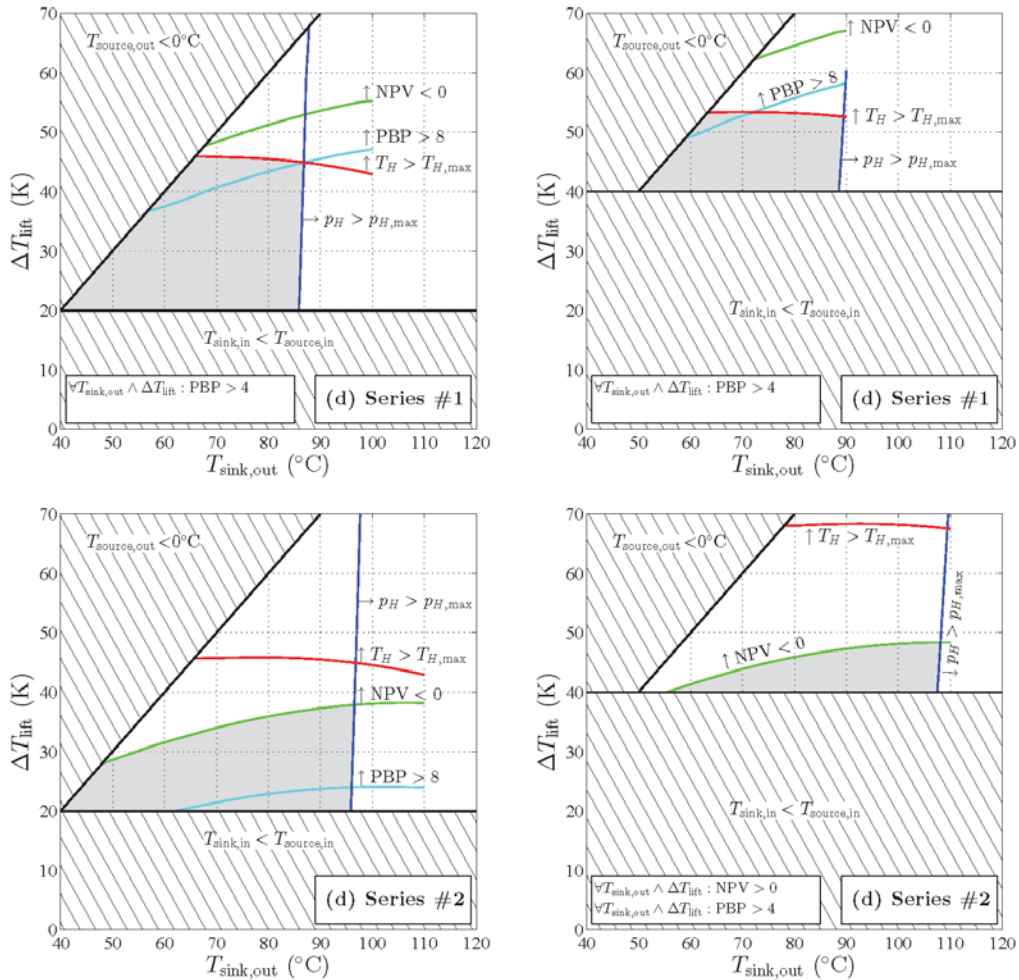

Figure 5: Feasible working domains indicated by grey background for serial connected vapour compression HPs. The considered temperature glides are (ΔT_{sink}/ ΔT_{source}) 20K/20K (a & c) and 40K/10K (b & d). Series #1 correspond to two R717-HP HPs, Series #2 correspond to R600a for unit 1 and R717-HP for unit 2.

5.   CONCLUSION

Four schemes for serial connection of industrial HPs were investigated in the paper. It is found that serial connection of either two or three units results in an increase in COP and a decrease in NPV, when compared to the reference system with only one HP. On the other hand, the serial connection reduces the discharge temperature, which is of particular interest when assessing R717 HPs. Another possibility is to mix different types of HP units, in order obtain specific characteristics. Both improvements result in enlarged working domains for both investigated dual unit serial connections.
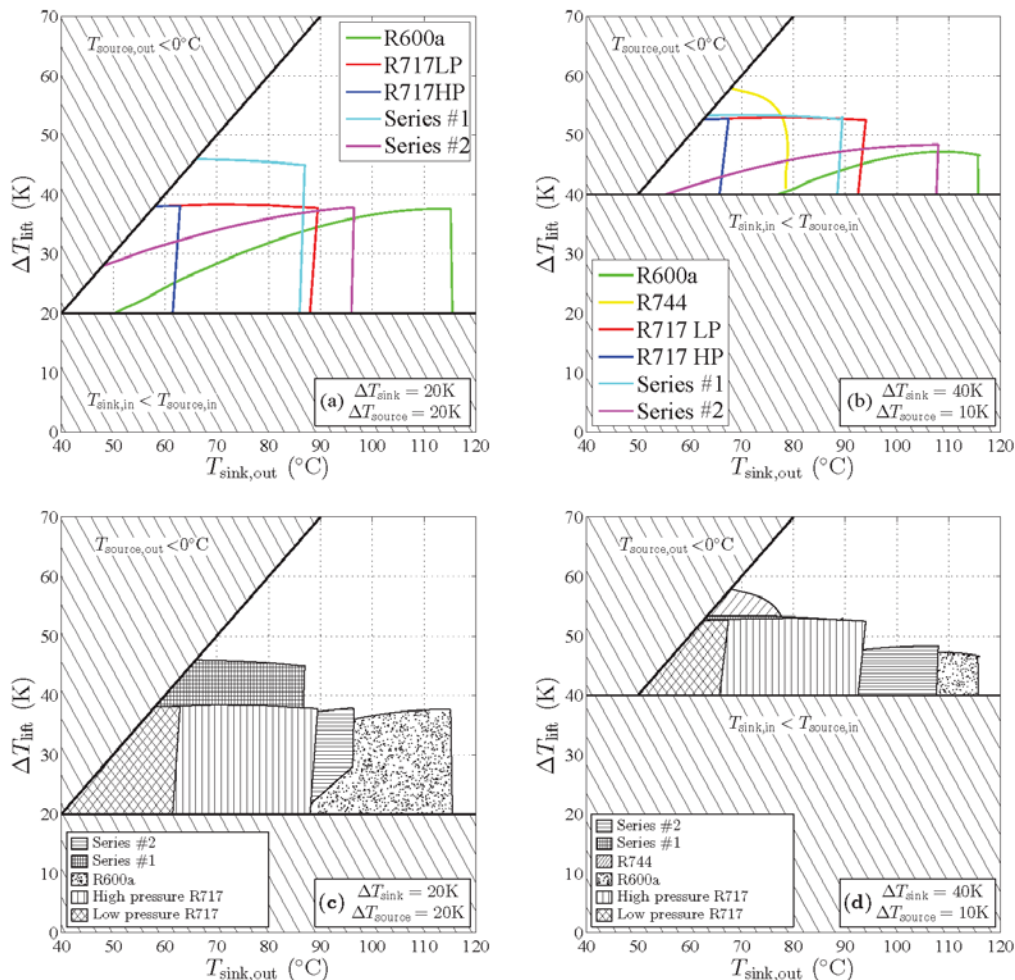
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Figure 6: Compilation of working domains (a & b) and hatched areas with most profitable vapour compression technology based on NPV (c & d). The considered temperature glides are (ΔT_{sink}/ ΔT_{source}) 20K/20K (a & c) and 40K/10K (b & d).

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