Techno-environmental comparison of steam generation systems with industrial heat pumps

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Abstract

Steam generation significantly contributes to the energy demand in industry since steam is widely used as energy carrier. To cope with energy efficiency measures, it becomes crucial to recover the waste heat as it is an inevitable product. Thus, the incorporation of a heat pumps might assist in this recovery for steam generation applications. In this work, the industrial steam generation with the aid of a heat pump is investigated. The integration of the heat pump into the process is realized for three main approaches: 1) direct steam generation, 2) steam generation with a flash tank and forced circulation and 3) steam generation with a drum for natural circulation. In the second approach, a circulation pump is needed. The last approach relies on natural circulation. This work conducts a simulation-based analysis to examine the performance of 4 configurations. The findings reveal a promising applicability of such systems with notable performance, which allows in promoting the energy efficiency measures in industry with great savings in CO_2 emissions compared to a conventional steam generation system (e.g. gas-fired steam generator).

Keywords: Heat pump, steam generation, natural circulation, flash tank, plate heat exchanger, plate and shell heat exchanger.

1. Introduction

Nowadays, the decarbonization of the industrial sector is broadly discussed and profoundly stressed out due to the increasing awareness against climate change, pollution and depletion of fossil fuels. Thus, several states began to introduce a set of policy measures in order to pave the way for a smooth transition to a low-carbon, sustainable and affordable energy future (Singh Gaur et al., 2021). If properly defined, such measures should ultimately lead to the decarbonization of the several energy sectors. Amongst others, industry sector arises as one of the most energy-intensive sectors that plays a significant role in emissions when fossil fuels are used (Kim, 2022). Thus, the industrial sector inevitably is no exception in any decarbonization plan. Subsequently, many states worldwide started embarking ambitious goals for expanding the share of renewable energy resources (RES) in their future energy system scheme. In this context, it is noteworthy to highlight that the share of RES is increasing in the electricity mix and, therefore, electrification might be a viable option for the aimed sustainable energy future (Kim et al., 2022).

Amongst others, industrial steam generation accounts for a significant share in the industrial applications due to its emergence as an interesting energy carrier for applications in which process heat is demanded and, subsequently, is extensively consumable in the industry (Liu et al., 2022). Often, steam (elevated temperature, superheated) is highly desirable in several industrial applications such as drying, refining and food processing. Steam can be offered for industrial applications by means of several methods: 1) offsite generation and transferred to demand side, 2) conventional boilers and 3) combined heat and power (CHP) systems (Kang et al., 2019). In the first method, steam might lose its quality when transported due to heat losses. As for conventional boilers, they exploit the combustion of natural gas and, subsequently, they contribute to greenhouse gas emissions (GHG). Likewise, CHP units might tend to use natural gas as fuel for large portion of its installations.

Noticeable is that the foregoing methods significantly rely on the combustion of fossil fuels (e.g. natural gas) to achieve high-temperature steam. This will lead to an increase in emissions with other drawbacks, e.g. violation to security of supply due to increase in gas prices as seen after Ukraine crisis. Inevitably, one of the key measures to achieve industrial decarbonization and independency from conventional fuels is the increase in energy efficiency measures for steam generation given its tremendous potential. In this context, waste heat recovery (WHR) arises as a promising measure for efficient steam generation due to its capability to utilize medium to elevated temperature heat sources for steam generation (Broberg Viklund and Johansson, 2014).

doi:10.18086/eurosun.2022.05.02 Available at http://proceedings.ises.org

Subsequently, heat pumps are commonly attractive solutions for enhancing process energy efficiency via waste heat recovery, lowering pollutant emissions, and improving the utilization of primary energy resources (Arpagaus et al., 2016). Thus, several policy makers have paid notable attention to such technology due to its key role in the achievement of sustainable energy future. In this regard, heat pump technology is powered by electricity to lift the heat captured from industrial waste heat at low temperature level to medium or elevated temperature level. Owing to its low environmental impact and desired energy efficiency, this work examines the potential of heat pumps assisted steam generation and quantifies four configurations for heat pump integration to achieve high steam quality.

2. Literature review

Despite the low expansion level for heat pumps in industry, adoption of such a technology is drastically increasing besides the soaring in the gas prices, which might later lead to undesired impacts (e.g. increase in product unit prices due to increase in OPEX). The significant importance of heat pump technology is owed to its potential to reduce emissions by reuse of industrial waste heat and use of electricity (or surplus electricity from RES) to lift the waste heat to higher temperatures and use it for industrial applications. As a result, it is anticipated that heat pump installation will witness a drastic deployment in the coming years.

In this context, steam generation with the aid of heat pumps has been widely discussed in several research studies. For instance, (Liu et al., 2022) recently suggested a new concept for high-temperature heat pumps for efficient and economic steam generation applications. The work revealed the capability of the proposed heat pump to produce steam with temperatures up to 154°C and this generation can be realized with a cascade energy inputs. Aiming at a novel high-temperature heat pump, (Mateu-Royo et al., 2019) proposed a layout with a modified scroll compressor and an internal heat exchanger. The work conducted a steam generation analysis with the refrigerant “HFC-245fa” and, accordingly, the heat pump was capable to produce steam with a temperature of 140°C.

On their part, (Meroni et al., 2018) paid considerable attention to the design of heat pump compressors in order to reduce the energy input with higher operation performance. The work presented a mean-line model for centrifugal compressors design, optimization and analysis. The model was later validated against a set of design and off-design conditions. The work revealed the potential of multi-stage compressor with steam as working medium for achieving the highest performance compared to other counterparts. For steam generation with the aid of heat pumps including a flash tank, (Chen et al., 2021) proposed such a system for deep recovery of waste heat and conducted a techno-economic analysis to show the potential and generation capacity of the suggested system. The outcomes highlighted the prominence of the proposed system for efficient and feasible recovery of the waste heat.

Owing to their importance, heat exchangers (i.e. condenser and evaporator) design is a crucial aspect in industrial heat pumps. This is attributed to the resulting heat transfer coefficient and the heat transfer area. In this regard, plate heat exchanger (PHE) found its place favorably in several industrial applications such as chemical processes and food processing due to its low cost and high heat transfer performance resulting from high heat transfer area to volume ratio for such heat exchangers and,, thus, PHEs are characterized with design compactness (Abu-Khader, 2012). Yet, PHEs are often limited in the operation range (temperature and pressure) and, thus, they are not suitable for high-temperature industrial applications (> 150°C). Besides, they are prone to fouling issues that might lead to impact on thermo-hydraulic behavior in heat exchangers. As a results, plate-and-shell heat exchangers (PSHE) are envisioned as alternative candidates to PHE to overcome the above-mentioned drawback. In this context, (Jo et al., 2020) experimentally compared both types in order to evaluate the evaporative heat transfer characteristics and address their applicability for industrial heat pumps employing R-1234ze(E) as a refrigerant. Compared to its PHE counterpart, the work concluded that PSHE showed better performance in terms of heat transfer.

To reduce the refrigerant temperature at the inlet of the throttling valve, an internal heat exchanger (IHX) is implemented in the heat pump system. The main goal of IHX is to transfer heat from the liquid refrigerant side to the vapor refrigerant side in order to boost the system performance and increase the temperature (or quality) of the steam (Cao et al., 2019). Accordingly, industrial heat pumps are equipped with an internal heat exchanger (IHX) to boost their performance. The work concluded a significant increase in the heating coefficient of performance when an IHX present in the heat pump cycle.

On the sink side, the lukewarm water can be circulated with the aid of either forced circulation or natural circulation. In the first method, a circulation pump is dedicated to accomplishing this task by steering the feedwater through the heat pump condenser to absorb the heat and eventually boils. Such a method has no segregation in the process and can be called “direct steam generation”. Natural circulation, on the other hand, is characterized with the presence of drums that captures the resulted mixture after the condenser and releases only saturated steam. The forced circulation can operate at higher pressures and temperatures, whereas the natural circulation has lower pressure drop. Yet, it is noteworthy to mention that the absence of drums and its equipment (i.e. downcomers and risers) make options with forced circulation more attractive due to lighter weight. Yet, the desire to decrease the operational expenditure drives the efforts to integrate drums in order to generate a pressure difference sufficient to naturally circulate the feed water.

In this context, (Keshavar et al., 2019) numerically studied the dynamics of natural circulation for heat recovery steam generation. The work investigated the role of the drum design parameters heat rate input and feed water flowrate on the steam quality. The work concluded that increasing the feed water flow rate results to a decrease in the steam quality when heat rate input kept constant. Whilst the increase in heat rate input with a constant feed water flow rate led to an increase in the steam quality. Yet, the foregoing study with existing literature (such as (Naim Hossain et al., 2022), (Bilde et al., 2019)) are all limited to the application of natural circulation for boilers.

Although the aforementioned studies identified significant results and contributed to the knowledge of heat pumps, the authors highlighted and discussed the shortcomings associated. In this study, the authors aim to investigate the steam generation with the aid of heat pumps in order to take advantage of the waste heat and recover it for further use. Thus, this work will conduct a simulation-based analysis to examine the performance of each of the proposed configurations for industrial steam generation (section 3.1).

3. Methodology

3.1. Configurations for industrial steam generation

This work examines the heat pump-assisted steam generation enabling the recovery of industrial waste heat. Thus, several configurations for the heat pump integration can be noticed to realize steam generation. These configurations are as below:

- Configuration a: A circulation pump (forced circulation) with a flash tank as shown in Figure 1,
- Configuration b: Direct steam generation whereby the condenser is a plate heat exchanger (PHE) with no flash tank as illustrated in Figure 2,
- Configuration c: Direct steam generation whereby the condenser is a plate-and-shell heat exchanger (PSHE) with no flash tank as presented in Figure 2, and
- Configuration d: Herein, the circulation pump is eliminated due to the natural circulation that is carried out with the aid of the drum, downcomers and risers. This configuration is displayed in Figure 3.

In this context, it is noteworthy to highlight that both configurations (b and c) are similar with main exception in the condenser type. To gain further insights, Figure 4 shows exemplary sketches to illustrate the difference between a plate heat exchanger and a plate-and-shell heat exchanger. Another remark is that configuration (d) is also similar to the sketch of configuration (a). Yet, the circulation pump and the flash valve are eliminated. The flash tank is substituted with a drum to realize the natural circulation. Figure 5 shows a typical industrial heat pump with all components used. Such a heat pump will be used for the configurations investigated in this work.

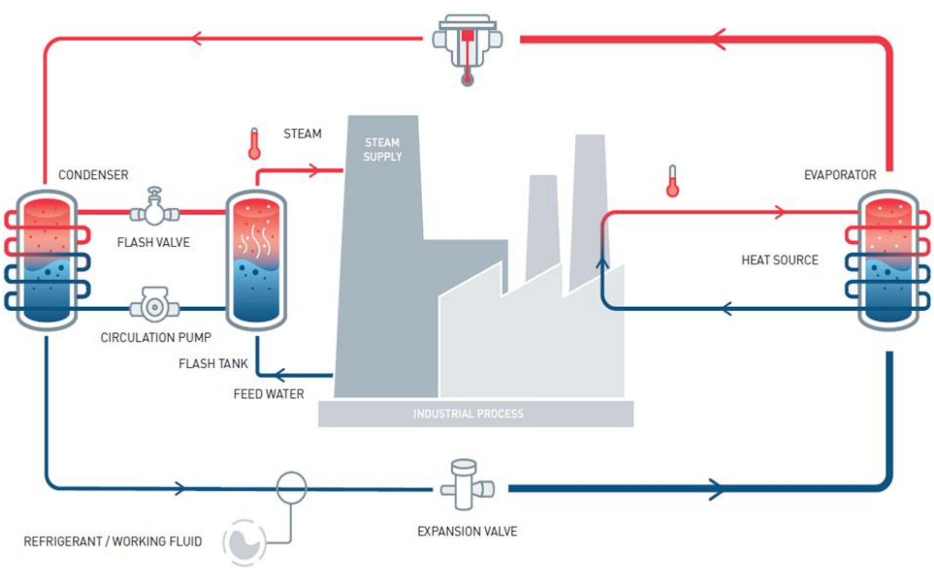

Figure 1: Steam generation with forced circulation and flash tank, configuration a.

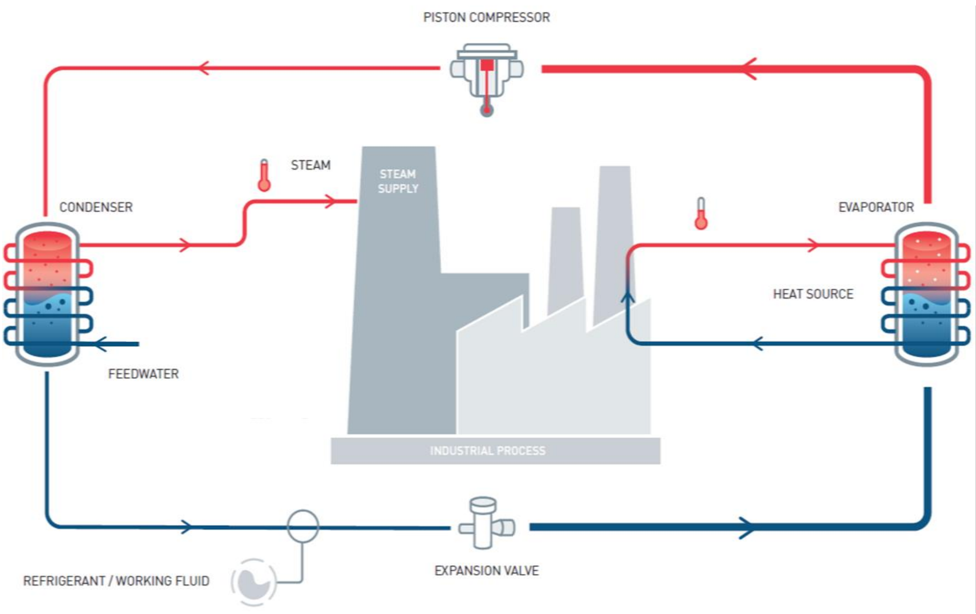

Figure 2: Direct steam generation without flash tank, configurations b and c.

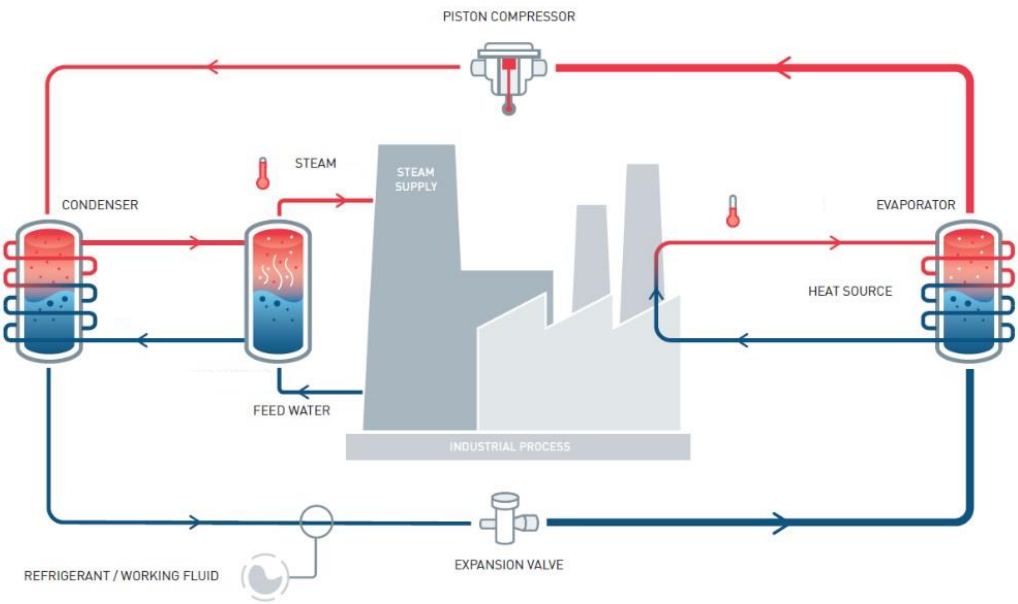

Figure 3: Steam generation with drum and natural circulation, configuration d.

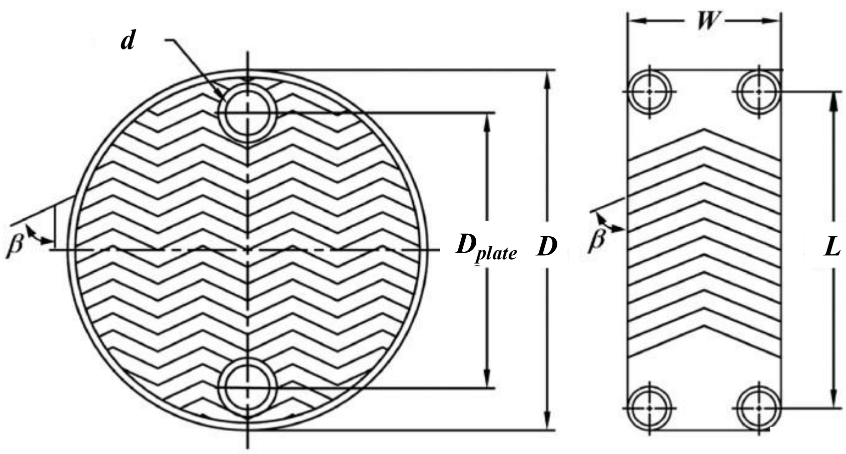

Figure 4: An exemplary sketch for the plate-and-shell heat exchanger (PSHE) and plate heat exchanger (PHE) (reproduced from (Jo et al., 2020)).

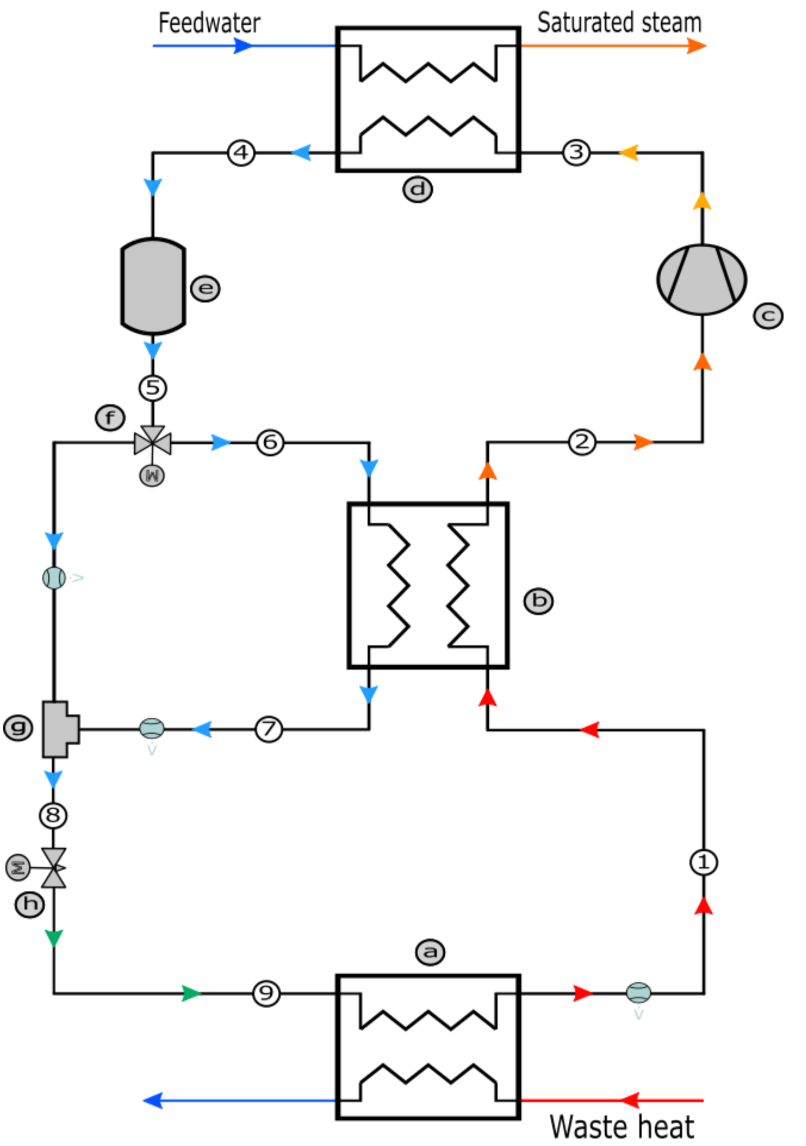

Figure 5: A typical industrial heat pump installation for the investigated configurations in this work. Heat pump components: (a) evaporator, (b) internal heat exchanger, (c) compressor, (d) condenser, (e) liquid/gas separator, (f) 3-way valve, (g) junction and (h) expansion valve.

3.2. Dynamic system simulations

For all configurations, the heat pump system together with the required components (e.g. drum, flash tank) are all modeled with the aid of the object-oriented, equation-based, open-source modeling language Modelica. To run the simulations, Dymola 2022x is used as simulation environment. For the system simulations, basic components (heat exchangers, expansion valve, separator) are used from the commercial library TIL 3.10.0 developed by TLK Thermo GmbH (Gräber et al., 2010) (TLK Thermo GmbH). This library is supported by a TILMedia to emulate the thermophysical properties for all working media (e.g. refrigerants, water/steam). With the aid of this library, other models (e.g. drum, compressor, flash tank, plate-and-shell heat exchanger) are developed in house. The developed models shall obey the energy conservation and mass balance.

Moreover, the drum model is developed with the two volumes since two distinct phases (i.e. liquid and vapor) are present in the component. Besides, it is presumed that there might be a non-ideal phase interaction between both phases and, thus, a thermal non-equilibrium state. Accordingly, the liquid phase might have a different temperature from that of the vapor one. Yet, both volumes can exchange heat and mass between each other. Besides, the model can consider the pressure difference due to friction inside the drum and the geostatic effects (i.e. impact of ports location). Furthermore, the developed drum model also includes a simplified form for momentum balance including the forces of static pressure, friction and gravity. In summary, the following assumptions are considered for the models development:

1. The system configurations shall operate under steady-state conditions,
2. The thermal losses in the evaporator, compressor, condenser, internal heat exchanger, drum and flash tank are neglected, and
3. Expansion is an isenthalpic process.

The reader is directed to (Gräber et al., 2010) in case further information is needed for modelling of the components. Plate and shell heat exchanger is thoroughly described in (Dusek et al., 2020).

3.3 System boundary conditions

This work investigates the foregoing configurations for a saturated steam generation (κ = 1) with a pressure of 2 bar$_a$ and saturation temperature of 120.2°C. The heat pump configurations all operate with R1233zd(E) as refrigerant owing to its low global warming potential (GWP) and high heat transfer coefficient resulting in lower heat transfer areas as demonstrated in (Dawo et al., 2022).

The industrial waste heat is available as hot water with a temperature of 70°C and allows for a decrease of 5 K over the source side (evaporator) and, subsequently, the flowrate is regulated. The evaporator is a PHE type with 140 plates made of stainless steel. Table 1 reports other geometrical characteristics for the chosen heat exchangers in the analyzed configurations. The water side has a heat transfer coefficient of 2500 W/(m^2.K), whereas the refrigerant evaporation heat transfer coefficient is set to 10,000 W/(m^2.K). Furthermore, this work presumes a zero pressure drop over the evaporator length for both sides. Moreover, the heat pump compressor is capable to achieve a maximum flowrate of 216 m^3/hour and a maximum outlet temperature of 140°C. The heat pump condenser type is subject to examination and, accordingly, its design is determined by the configuration.

Table 1: Geometrical characteristics of the heat exchangers used in the configurations of heat pump.

Parameter	**Evaporator**	**IHX**	**Condenser**		
			Confs. (a, c)	**Conf. (b)**	**Conf. (d)**
Type	PHE	PHE	PHE	PSHE	PHE
Plate width, *W*	304 mm	364 mm	304 mm	364 mm	364 mm
Plate length (port to port), *L*port	601 mm	284.5 mm	597 mm	284.5 mm	284.5 mm
Angle of the corrugation, β	35°	35°	35°	89°	35°
Corrugation pitch	12.6 mm	12.6 mm	12.6 mm	1.2 mm	12.6 mm
Number of plates	140	40	120	114	150
Plate diameter, D_{plate}	-	-	-	440 mm	-
Shell diameter, *D*	-	-	-	732 mm	-

The investigated exemplary system demands a predefined superheating temperature of 15 K for the refrigerant at the inlet of the condenser. Thus, there is an IHX used in order to respect this this constraint (15 K). Consequently, it is crucial to implement a bypass that allows the refrigerant to proceed flowing to the throttling valve without passing through IHX if the constraint violated (> 15 K). This means that the condenser inlet temperature has a higher priority than that of the throttling valve. Moreover, the heat pump system comprises a separator post to the condenser to ensure a liquid refrigerant flow prior to the evaporator.

The configuration (d) with natural circulation encompasses a vertical drum component with a total length of 2.4 m. The downcomer port is located at 0.1 m, whereas the riser port is situated at a height of 2.1. The feed water inlet port is located at 0 m and the steam outlet port is at 2.4 m.

3.4 Performance indicators

In order to evaluate the technical capability of the configurations, the work analyzes the heat pump configurations by two performance indicators; one is the coefficient of performance (COP) for the heat pump integrated and the other is steam generation rate. All solutions that violate the constraint of compressor outlet temperature will be disregarded.

For heating applications, the coefficient of performance is the quotient of the useful heat delivered at the condenser (Q_{cond}) to the electricity input to the compressor (W_{comp}). Accordingly:

$$COP_{\mathrm{h}} = \frac{Q_{\mathrm{useful}}}{W_{\mathrm{in}}} = \frac{Q_{\mathrm{cond}}}{W_{\mathrm{comp}}} \quad (1)$$

4. Results and discussion

This study addresses a simulation-based analysis of heat pump configurations for steam generation. The simulations are conducted in Dymola 2022x environment with DASSL solver and a tolerance of 10^{-4}. In order to ensure a steady-state operation condition, the simulation time is set to a single day (24 hours). The goal of this analysis is to achieve a saturated steam at a temperature of 120,2°C and a pressure of 2 bar_a.

4.1 Heat pump cycle

Figure 6 reveals the log(*p*)-*h* diagram of the refrigerant R1233zd(Z) circulating in the heat pump. Noticeable is that all configurations had comparable refrigerant cycles with similar characteristics (e.g. temperature, pressure) despite the slight differences (< 1%). For instance, it can be observed that the pressure ratio for the used refrigerant remained at a value of appx. 3.78 for the configurations (a) and (c) whereby the evaporator and condenser pressures were 4.4 bar_a and 16.7 bar_a, respectively. This pressure ratio dropped down to 3.73 and 3.7 for the configurations (b) and (d), respectively. However, it was possible for all configurations to comply with the compressor outlet temperature constraint (< 140°C). For example, configuration (a) achieved a compressor outlet temperature of 138°C, whereas configuration (d) attained a value of 137°C. Despite this slight difference, all configurations led to a condenser outlet temperature of 123°C corresponding to a fully liquid refrigerant.

Furthermore, Figure 6 illustrates that the refrigerant further cooled down to (294.7 kJ/kg and 75.85°C) over the internal heat exchanger releasing a portion of heat (Δh_{IHX} = 66.5 kJ/kg) to the vapor refrigerant side. Yet, the outcomes highlighted that only a small portion of the refrigerant mass (13%) was directed in the IHX path, whilst the remainder (87%) flowed further to the junction component and remixed with the rest (13%) (compare Figure 5). Subsequently, such a behavior was obvious in the heat pump cycle as both flows mixed resulting in an enthalpy with a value of 352 kJ/kg. Post to the junction, the refrigerant expanded in the throttling valve leading to a refrigerant in a vapor phase with a quality of 43% for the configurations investigated.

By virtue of the waste heat (5 K, 21 kJ/kg and 4.14 kg/s), the refrigerant with 43% vapor quality absorbed this heat over the evaporator and, thus, it was slightly superheated. Later, the refrigerant received more heat through IHX and superheated further. In summary, the heat pump cycle could achieve a heating COP of 3.1 for all configurations investigated. Moreover, the cycle analysis pinpointed the role of IHX in the heat pump cycle and showed its minor impact in the entire operation and, thus, further work should consider and estimate the cost-to-benefit for such a component in steam generation heat pumps. Furthermore, the analysis showed that the changes in the heat pump configuration (e.g. PHE or PSHE) did not lead to significant changes on the refrigerant side under the considered boundary conditions (i.e. operational and geometrical).

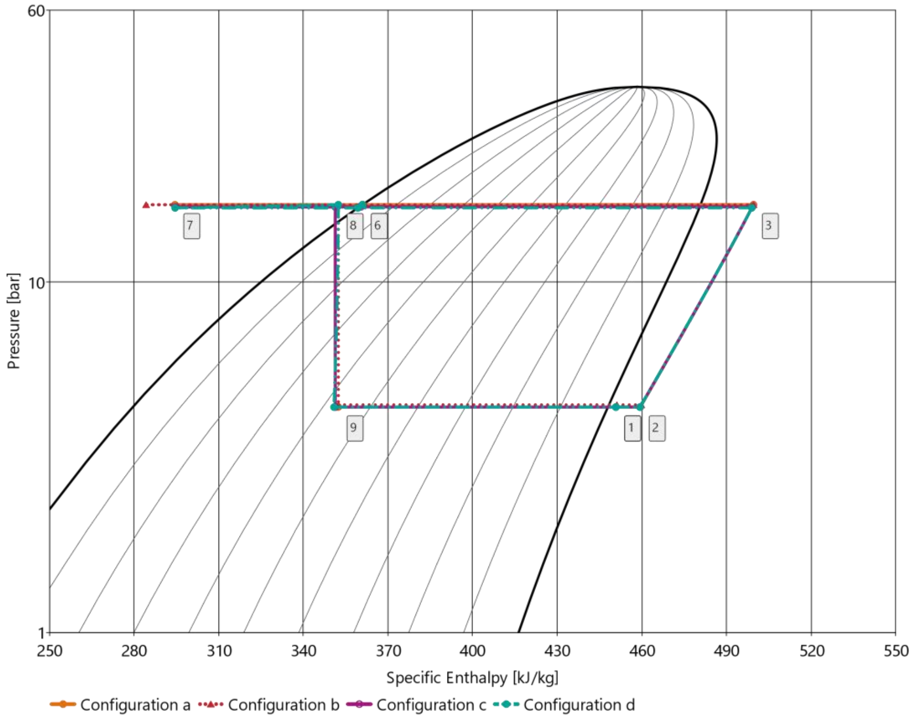

Figure 6: The log(p)-h diagram of the R1233zd(E) for the proposed steam generation heat pump configurations.

4.2 Steam generation analysis

Bearing in mind that the configurations showed no meaningful change in the heat pump cycle, it becomes crucial to evaluate the steam generation rate and its quality for the configurations investigated. For steam generation, the configurations were all supplied with feed water at a pressure of 2 bar_a and a temperature of 20°C (84.4 kJ/kg). Besides, it is worthwhile to inspect the geometrical parameters of the heat pump condenser to gain further insight into the heat pump suitability for steam generation.

Table 2: Summary of heat pumps configurations considered in this work for steam generation.

	Configuration (a)	Configuration (b)	Configuration (c)	Configuration (d)
Heating COP	3.1	3.1	3.1	3.1
Steam generation rate [kg/hr]	169	166	169	167
Condenser heat transfer area [m^2]	22.7	22.7	18.5	22.7
Circulation	Yes (Forced)	No	No	Yes (Natural)

The outcomes indicated the application of the steam generation configurations and they resulted in a similar generation rate with slight deviation (< 1%). In this context, both configurations (a) and (c) produced highest steam rate, but main difference was the condenser design. For configuration (a), a PHE with a heat transfer area of 22.7 m^2 was used, whereas configuration (c) included a PHSE condenser with a heat transfer area of 18.5 m^2. Besides, configuration (a) incorporated a flash tank and a circulation pump, whilst (c) did not. Despite the notable layout differences, both configurations led to comparable results (COP and steam). Moreover, it must be mentioned that the material volume used for heat exchangers manufacturing is surely of high importance as less volume demanded means lower investment costs.

The work also investigated a heat pump system with natural circulation (configuration (d)). Compared to its counterparts, such a configuration led to a generation of saturated steam with 167 kg/hour and a comparable COP. In such a configuration, a PHE with 120 plates and total heat transfer area of 22.7 m^2 was used at the sink side (i.e. condenser). Thus, it was possible to control the quality of the steam generated and ensured a statured steam. Herein, it must be mentioned that a drum was an essential component in this configuration in order to realize the natural circulation and eliminate the circulation pump.

4.3 Impact of evaporator temperature on steam generation

To understand the impact of the evaporator temperature difference on the steam generation rate, it is important to investigate a configuration that shows complexity. Therefore, this work considers configuration (a) for further analysis. Herein, the configuration composes of a heat pump system coupled to a flash tank with a forced circulation through the condenser. The foregoing analysis presumed a temperature difference of 5 K for the waste heat over the evaporator. Thus, this examination is extended to consider two other temperature differences of 10 K and 15 K over the evaporator, whereas the flowrate of water (i.e. waste heat carrier) is reduced to maintain a constant heat rate over the evaporator. Such a variation in temperature might be observable depending on the application. Moreover, other boundary conditions will be maintained.

In this context, Figure 7 shows the heat pump cycle for the configuration (a) under the analyzed boundary conditions for the variants of 5 K, 10 K and 15 K. Obviously, the decrease in temperature downstream the condenser leads to a notable change in the evaporator pressure as depicted in Figure 7. This is attributed to the control of the heat pump as it is required to maintain a superheating temperature of 3 K post to the evaporator on the refrigerant side. Thus, it is crucial to operate the heat pump at lower pressures to comply with this constraint.

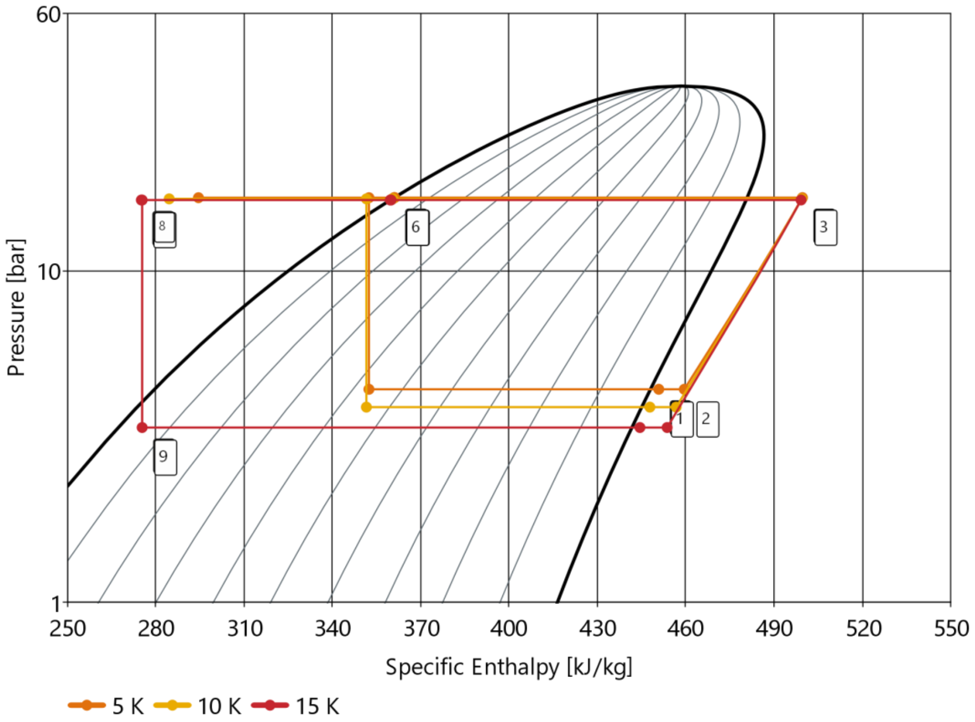

Figure 7: Impact of evaporator temperature difference on the heat pump cycle of configuration (a).

The increase of useful temperature difference from 5 K up to 15 K leads to a remarkable decrease in the refrigerant velocity as shown in Figure 8. This inevitably means that the refrigerant at the evaporator upstream is denser as the temperature difference increases. For instance, when considering the 15 K variation, the refrigerant has higher density and accordingly lower steam quality to that of the 5 K variation. This is evidently revealed in Figure 7. Inevitably, this decrease in refrigerant velocity will eventually lead to an increase in the compressor pressure ratio to fulfill the requirements of 15 K as superheating temperature with a maximum temperature of 140°C for the condenser upstream. Thus, compressor power input will increase and, consequently, this increases the operational expenditure.

Moreover, the outcomes revealed a decrease in heating COP from 3.1 for the 5 K variation down to 2.8 for the variation of 15 K. The heating COP is 2.9 for the 10 K variation. In this context, noticeable is the reduction that occurs in the steam generation rate as it drops from 169 kg/hr for 5 K variation down to 119 kg/hr for variation of 15 K, whereas a rate of 144 kg/hr is obtained for 10 K variation. The quality and temperature of the produced steam remain for all variations as required (i.e. saturated steam at 2 bar_a and 120.2°C).

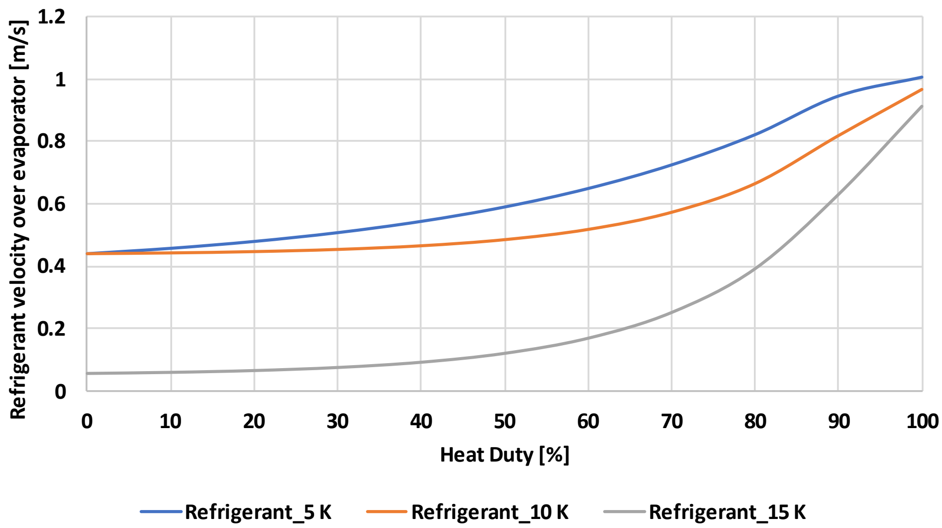

Figure 8: Refrigerant velocity over the length of a single plate in the evaporator.

4.4 Environmental analysis

In order to understand the environmental impact of steam generation with the aid of industrial heat pumps, it is essential to compare the emissions produced against a conventional system. In this manner, the foregoing findings underline that the heat pump condenser has a heating rate of 125 kW to produce steam with a rate of 166 kg/hr – 170 kg/hr. Thus, a gas-fired steam generation with a heating power of 125 kW and efficiency of 90 % arises as a conventional candidate that is used as a benchmark.

For the environmental analysis, the carbon dioxide emissions can be determined:

$$M_{\mathrm{CO_2}} = f_{\mathrm{CO_2}} \cdot E \qquad (2)$$

Herein, $f_{\mathrm{CO_2}}$ represents the annual averaged emission factor in [kgCO2/kWh] following the Austrian guidelines for each energy form, whereas E stands for the annual energy consumption required in [kWh/a] for steam production. Heat pumps consume electricity from the power grid and, thus, the emission factor is 219 kg_{CO2}/kWh_{el} (Umweltbundesamt GmbH, 2021). The conventional system, on the other hand, consumes natural gas with an emission factor of 268 kg_{CO2}/kWh_{gas} (Umweltbundesamt GmbH, 2021). To determine the annual energy consumption, it is assumed that an industrial plant runs for 7320 hours/a, and the rest is for maintenance. Accordingly, **Table *3*** reports the savings in carbon dioxide emissions for heat pumps steam generation systems compared to the conventional system. Therein, it is obviously seen that a total of 208 tCO_2 can be saved on annual basis when heat pumps selected for steam generation.

Table 3: Summary of environmental analysis between steam generation with aid of heat pumps and a gas-fired steam generation.

System	Steam generation rate [kg/hr]	Heating power [kW]	Annual electricity [MWh_{el}/a]	Annual Gas consumption [MWh_{gas}/a]	Annual CO_2 emissions [tCO_2/a]
Heat pump steam generation	166 – 170	125	295	-	64.5
Gas-fired steam generation	170	125	-	1016.5	272.5

5. Conclusions

Process heating plays a significant role in the industrial energy demand whereby 20% of this process heating is required at temperatures between 100°C and 200°C. For such a temperature range, steam arises as an interesting energy carrier for industrial applications. Besides, the importance of steam emerges from its application as heat transfer medium and reaction medium as well. However, steam generation might be costly and unfriendly for environment when conventional fuels are used. In order to increase the energy efficiency measures and reduce the CO2 emissions, the use of waste heat is required.

In this work, 4 configurations for steam generation with the aid of heat pumps were investigated with the aid of numerical simulation in Modelica/Dymola. The configurations were: (a) direct steam generation with a HP equipped with a plate-type condenser, (b) direct steam generation with a HP equipped with plate and shell-type condenser, (c) steam generation with a HP coupled to a flash tank and a circulation pump and (d) steam generation with a HP coupled to a drum to realize natural circulation allowing the elimination of the circulation pump. For the analysis, the aim is to supply industry with saturated steam at 2 bar_a and 120°C.

The refrigeration cycle analysis revealed same heating coefficient of performance ($COP_{heating}$) for the heat pumps in the investigated configurations. The findings revealed that those configurations slightly differed from each other with the amount of steam generated. Compared to its counterparts with plate-type condenser, configuration (b) showed smaller heat transfer area with a reduction of 19 % for the heat pump condenser due to the implementation of a plate-and-shell heat exchanger. Thus, this reduced the land availability, which is an important aspect considered by industry of installation.

Moreover, the work conducted a comparison against a conventional steam generation system (i.e. gas-fired steam generator with 90% efficiency) to examine the environmental impact of steam generation with heat pumps. The outcomes showed significant CO_2 savings of around 80% when heat pumps used for steam generation compared to gas-fired steam generator under same boundary conditions.

6. Acknowledgments

The project has received funding from the European Union’s Horizon 2020 programme for energy efficiency and innovation action under grant agreement No. 820771.

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