International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2002

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Ferreira, C. A. Infante and Zaytsev, D., "Experimental Compression – Resorption Heat Pump For Industrial Applications" (2002). *International Refrigeration and Air Conditioning Conference.* Paper 601.
http://docs.lib.purdue.edu/iracc/601

EXPERIMENTAL COMPRESSION – RESORPTION HEAT PUMP FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

Wet compression - resorption heat pumps are a promising type of heat pumps that operates with non-azeotropic refrigerant mixtures. The main differences, when compared to the classical Rankine cycle, are the non-isothermal phase transition of the mixture in the heat exchangers and the compression of the two-phase mixture in the compressor, which works as a gas compressor and at the same time as a liquid pump. Wet compression results in reduction of the consumed power, excludes the vapour superheating and is especially attractive for high temperature applications. For such applications estimated gain in COP is up to 20% when compared to conventional dry compression heat pumps.

A 50 kW experimental ammonia water heat pump of this type has recently been taken in operation. It has been designed to upgrade a water flow from 110 to 130°C, using a water waste flow with 80°C. The resorber and desorber are of the falling film vertical shell-and-tube type, with the ammonia water film inside the tubes and a distribution system in the top header. The intermediate heat exchanger is of the shell-and-plate type. Oil-free wet compression of ammonia water was obtained with an especially designed twin-screw compressor. Details and performance results of this compressor are discussed in a parallel paper.

This paper discusses the experimental set-up design and the experimental data of resorber, desorber and intermediate heat exchanger.

INTRODUCTION

Compression - resorption heat pumps have the potential to give significant contributions to the improvement of the energy performance of heating processes. Specifically for industrial heating processes they allow for energy performance gains of more than 20% when compared with vapor compression heat pumps.

Ammonia-water high temperature heat pumps that are used to upgrade industrial waste heat show a number of advantages:

- High temperature operation is possible at relatively low operating pressures
- The cycle can be designed to show a temperature glide in the resorber that corresponds to the temperature glide of the industrial waste flow that has to be heated.
- For specific operating conditions the cycle performance is significantly beter than for the vapor compression cycle.

There are two types of compression - resorption heat pumps: with solution circuit (liquid pump and saturated vapor compressor are used to overcome the pressure differential) and with two-phase (wet) compression. Here the compressor simultaneously compresses the vapor and increases the liquid pressure. Itard [1998] has shown that, specially for high temperatures, wet compression leads to higher energy efficiencies than the solution circulation alternative. Next to this energy advantage, wet compression also allows for higher operating temperatures. Dry compression in the solution circulation variant leads to large superheating temperatures of the vapor and associated problems and exergy losses.

A large number of theoretical and experimental studies have been dedicated to the solution circulation variant of the compression - resorption heat pump cycle (reviewed by Groll [1997]). On the opposite only a few studies / experimental set-ups have been dedicated to wet compression cycles (Malewski [1988], Bergmann [1990], Torstensson [1991], Sixt [1995] and Itard [1998]). The main problem of the cycle is the compressor that has to be suitable for oil-free wet compression and still show acceptable isentropic efficiencies. Torstensson and Sixt used oil-lubricated compressors without oil recovery. Torstensson used a scroll compressor while Sixt used a wankel compressor. In both cases the lubricant circulated together with the solution through the whole system reducing the efficiency of resorber and desorber. Malewski used a monoscrew compressor with closed grease bearing lubrication and separated liquid injection at intermediate pressure. Itard used a liquid ring compressor. Bergmann used an oil-free twin-screw compressor with timing gears with separated liquid injection at suction and intermediate pressure conditions. In the present study also an ammonia-water twin-screw compressor with liquid injection has been used but no timing gears are used. The gaps between rotors and between rotors and housing are smaller and the male rotor drives the female rotor. The bearings are oil lubricated and separated from the process side by radial lip seals.

EXPERIMENTAL SET-UP

Making use of Itard's [1998] experience, her experimental set-up has been rebuilt to allow for high temperature operating conditions to upgrade industrial waste heat. The design operating conditions have been selected to allow for application as heat pump for heating of waste water flows from 110 to 130°C in food processing plants. The design conditions are listed in Table 1.

Figure 1: Ammonia water high temperature compression resorption heat pump set-up

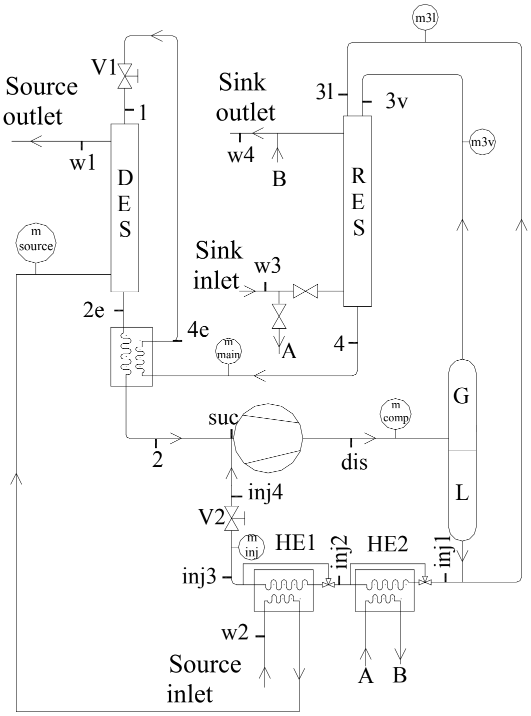


Figure 2: Schematic diagram of experimental set-up

Table 1: Design conditions for experimental set-up.

Heating power	50 kW
Heat sink water in	110°C
Heat sink water out	130°C
Heat source water in	80°C

Figure 1 shows the experimental set-up, before it has been insulated. The two vertical shell-and-tube heat exchangers are the resorber and desorber. The work medium is ammonia water. The average ammonia concentration is 35%. A schematic of the experimental set-up is given in figure 2.

The liquid / vapor mixture leaving the compressor is first separated to allow for liquid injection. Liquid and vapor flow to the resorber through separate lines. Heat is recovered from the injection liquid into the sink and source flows before being injected into the compressor. This allows for an increase in heating capacity (sink flow) and a higher desorber operating pressure. An internal heat exchanger of the shell-and-plate type is used between resorber and desorber. Table 2 gives some details about the components and system.

Table 2: Components and system details.

Component / Detail	Type	Flow pattern	Size
Resorber	Vertical shell-and-tube	Falling film, length = 1.5 m	9.87 m²
Desorber	Vertical shell-and-tube	Falling film, length = 1.5 m	9.87 m²
Internal heat exchanger	Shell-and-plate	Single phase / boiling	2.91 m²
Compressor	Twin-screw		82 m³/h
Injection line heat exch.	Plate	Single phase / single phase	0.75 / 1.25 m²
System contents	Ammonia water		40 liter
Filling concentration			35% wt
Low pressure side			2 bar
High pressure side			16 bar

The resorber, desorber and internal heat exchanger are mild steel heat exchangers. Vertical falling film shell-and-tube heat exchangers have been selected instead of the aluminum compact heat and mass exchangers used by Itard to allow for high temperature operating conditions. A special distribution design on the top header of resorber and desorber allows for even distribution of the liquid as a film inside each of the 166 tubes with 9.9 mm internal diameter.

During the experiments, the flow rate of the rich solution to the desorber was adjusted with expansion valve V1 so that the ammonia vapor is completely absorbed at the outlet of the resorber. This can be visualized through a sight glass at the resorber outlet and guarantees that liquid leaves the resorber at almost saturation conditions (slightly subcooled).

Two flow / density meters at the liquid inlet and outlet of the resorber allow for continuous concentration measurements of the weak and strong solution. Pressure and temperature sensors and mass flow meters allow for first law analysis of each of the main system components. Instrumentation around the compressor is discussed in a parallel paper (Zaytsev and Infante Ferreira [2002]).

Insulation losses

The experimental set-up has been insulated with 40 mm shells of rock fiber. Since the experimental set-up is located in a continuously ventilated space with a slightly lower pressure than the environment, the air flow leads to relatively high heat transfer losses through the insulation. These losses have been calibrated by bringing the whole set-up to a certain temperature level and measuring the heater input requirement. Fig. 3 shows the insulation losses per component as a function of the operating temperature level.

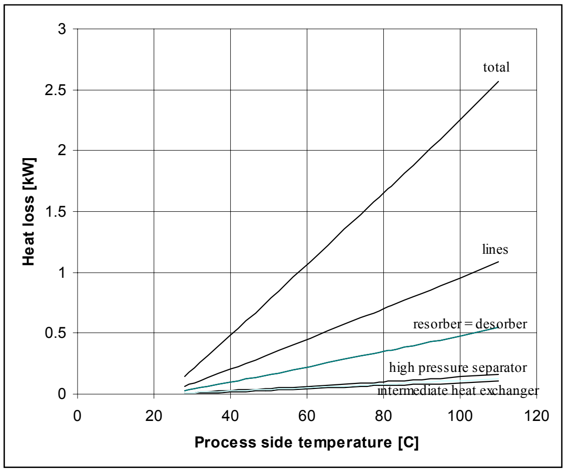


Figure 3: Heat losses through insulation.

Figure 3 shows that at part load conditions, the heat losses can be very significant and will play an important role in the COP's that can be attained.

EXPERIMENTAL RESULTS AND DISCUSSION

Typical operating conditions

The working conditions of the experimental set-up are illustrated for a specific experiment in figure 4 in an enthalpy – concentration diagram for ammonia water.

From figure 4 it becomes clear that during compression some ammonia vapor is absorbed into the liquid flow. The liquid concentration increases from 30% at compressor injection conditions to 31% at compressor outlet conditions.

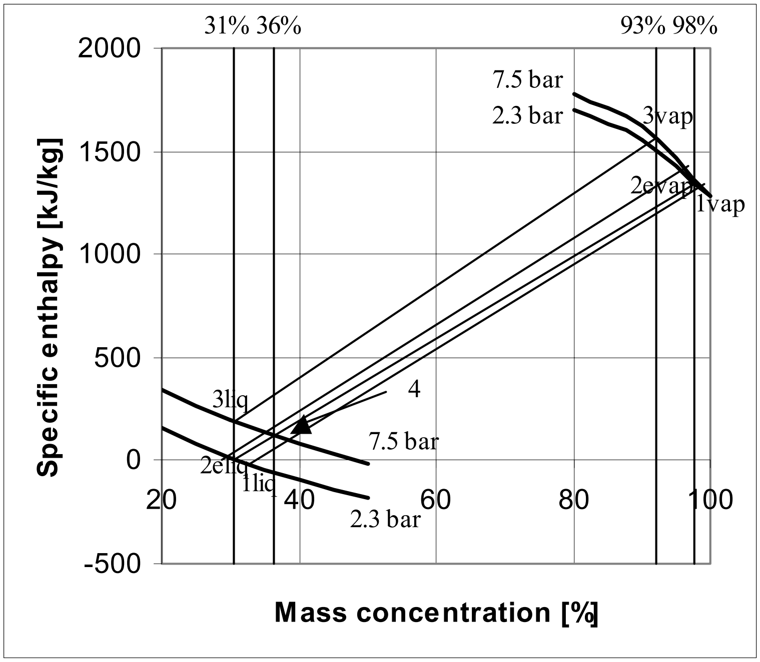


Figure 4: Specific enthalpy – concentration diagram of ammonia water showing the operating points in the system. For positions in cycle refer to fig. 2.

For most of the experiments reported here, the difference in concentration between strong and weak solution ranged from 8 to 12%, depending on the operating conditions. Part of the desorption process takes place in the intermediate heat exchanger.

Resorber performance

Two sets of experiments have been executed: one with low water flow (0.24 kg/s) and one with high water flow (0.48 kg/s). With the low water flow the temperature glide of the water flow approached the temperature glide in the ammonia water side of the resorber. In both cases the temperature driving forces are significant. The temperature profiles are schematically illustrated for two experiments in figure 5.

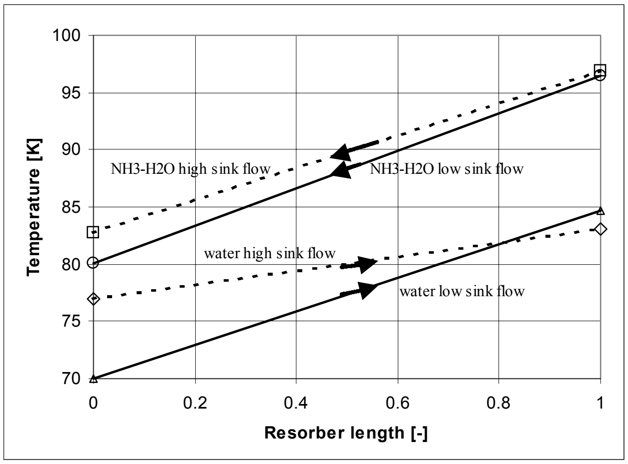


Figure 5: Experimental resorber temperature glide.

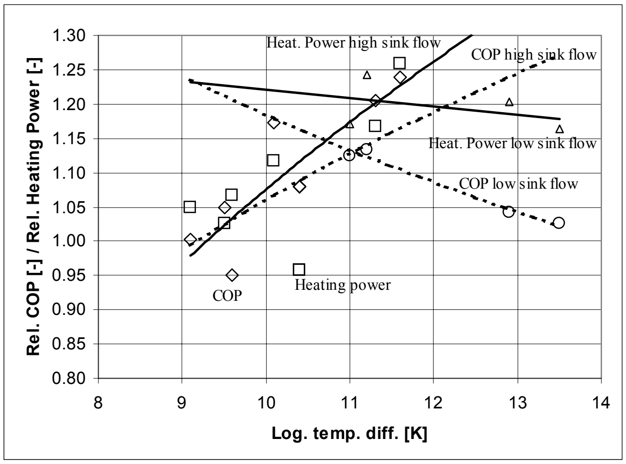


Figure 6: Variation of the relative COP and heating power of the resorber with the temperature driving force.

Figure 6 shows that for large water flows the COP and heating power increase significantly with the resorber temperature driving force. The COP increases 5 to 10% per K temperature increase while the heating power increases about 10% per K. For low water flows both the COP and heating power decrease when the resorber temperature driving force increases. Low water flows lead to low water side heat transfer coefficients in the resorber and consequently to higher discharge pressure for the compressor and associated lower COP for the system. The large decrease in COP shown in figure 6 is enhanced by an increase in sink temperature for the higher temperature driving forces.

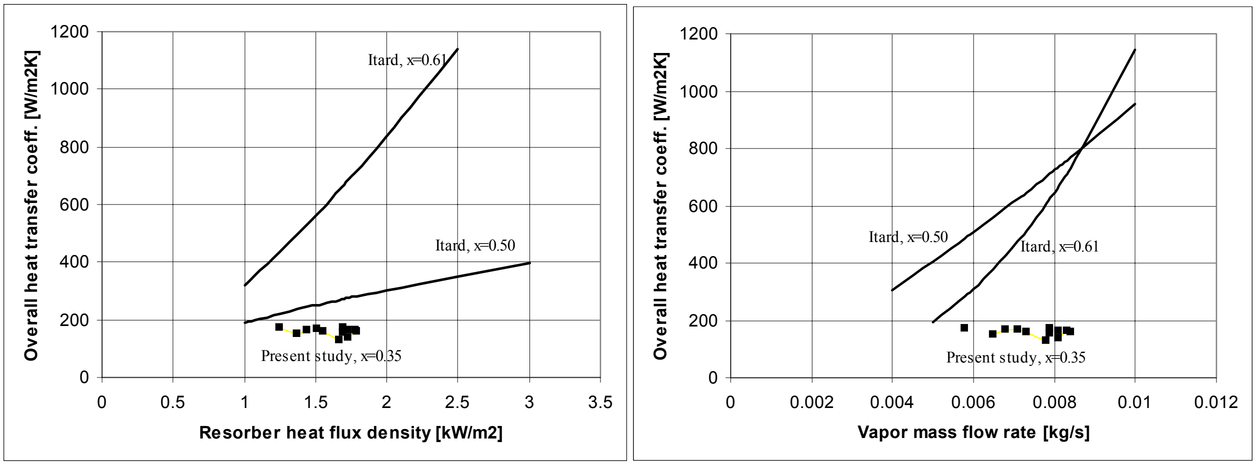


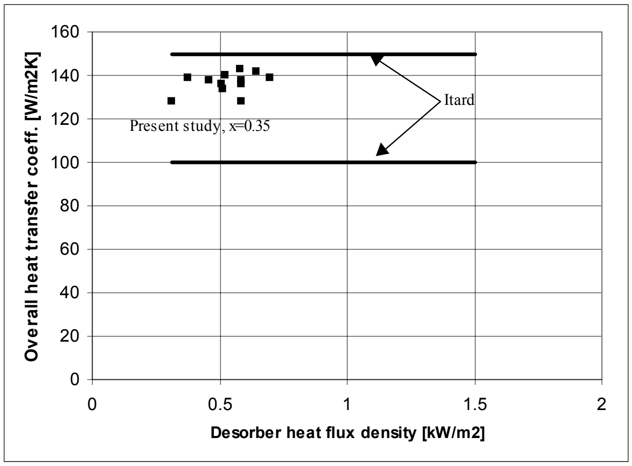
Figure 7: Experimental resorber overall heat transfer coefficient.

Figure 7 shows the experimental resorber heat transfer performance in comparison with the experimental data obtained by Itard [1998] for a plate fin resorber.

The experimental results show that the overall heat transfer coefficients are rather small but, taking into account the relatively low ammonia water concentration, comparable with the results reported by Itard [1998] for a plate fin resorber. When the distribution would be ideal, the expected film thickness is extremely small: 0.1 mm and the liquid film Reynolds number is also very low: smaller than 25. The low heat transfer performance indicates that the distribution system needs improvement.

Desorber performance

Figure 8 shows the experimental desorber heat transfer performance. These values are of the order of magnitude of the experimental data obtained by Itard [1998] for a plate fin desorber (between 100 and 150 W/m2K). As in Itard's experiments the heat flux density is very low since the compressor has been operating under part load conditions during the experiments reported here.



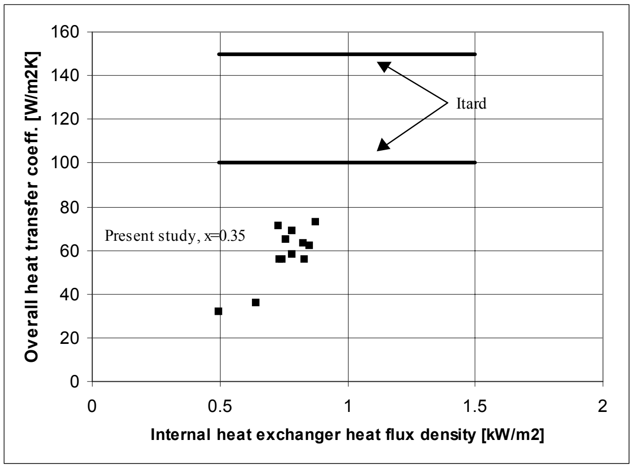


Figure 8: Experimental desorber overall heat transfer coefficient.

Figure 9: Experimental internal heat exchanger overall heat transfer coefficient.

Internal heat exchanger performance

Figure 9 shows the experimental internal heat exchanger performance. The heat transfer coefficients for the shell-and-plate heat exchanger are very low. To allow for the vapor developed in the heat exchanger to be removed with the flow, the plates have been installed horizontally. For the two points with heat transfer values lower than 40 W/m²K, the ammonia water flow is smaller.

CONCLUSIONS

The characteristics of an experimental ammonia water compression resorption heat pump have been discussed. Experimental data of the resorber showed that the maximum system COP is not always attained for an ideal matching of the temperature glide of the process and sink sides in the resorber. The heat transfer performance of the resorber and desorber is poor, most probably because the liquid distribution needs improvement and partly because the system has been operated under part load conditions. The shell-and-plate intermediate heat exchanger shows extremely low heat transfer performance.

ACKNOWLEDGEMENTS

This research has been funded in part by the European Commission in the framework of the Non Nuclear Energy Programme JOULE III contract JOE3-CT97-0079. The authors also would like to thank Roland Süss and Calin Zamfirescu for their contribution to the design of the test plant and data processing system.

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