Effect Of Operational Parameters On Heat and Mass Transfer In Generator of R134a/DMF Absorption Refrigeration System

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Effect of operational parameters on heat and mass transfer in generator of R134a-DMF absorption refrigeration system

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ABSTRACT

Vapour absorption refrigeration systems (VARS) has regained the attention due to their potential for renewable/waste heat utilization. To improve the efficiency of these systems, it becomes obligatory to make component level studies on processes. In this present study, investigations on the heat and mass transfer in compact generator of the vapour absorption refrigeration system have been carried out using R134a-Dimethyl formamide (DMF). An experimental facility of VARS has been fabricated using brazed plate heat exchangers as generator, condenser, absorber, evaporator and solution heat exchanger. Hot water source is used to supply hot water between 80 °C and 98 °C to suit utilization of solar energy, waste heat, etc to the generator. Cooling water from cooling water source is circulated through the absorber and condenser to remove the heat. Water from cooling load simulator is circulated to the evaporator. Investigations have been carried out on VARS with a rated cooling capacity of 1kW by varying the operating parameters viz, solution flow rate from 0.02 m³/hr⁻¹ to 0.05 m³/hr⁻¹, liquid refrigerant flow rate from 0.002 m³/hr⁻¹ to 0.015 m³/hr⁻¹, hot water temperature from 85 °C to 97 °C. Generator pressure is varied from 620 kPa to 920 kPa, hot water flow rate from 0.12 m³/hr⁻¹ to 0.32 m³/hr⁻¹ and solution initial concentration is varied from 0.59 kg/kg⁻¹ to 0.75 kg/kg⁻¹. The effect of solution flow rate, generator temperature and generator pressure on the performance of generator and the absorption system has been investigated. Heat and mass transfer coefficients, heat transfer rate, mass desorption rate increase with generator temperature and solution flow rate but decrease with increase in generator pressure.

1. INTRODUCTION

Many researches are carried out in absorption refrigeration technology, in the recent years, aiming to search for environment friendly alternate working pairs and to improve the efficiencies of various major components of the vapour absorption refrigeration system. Even though traditionally used working fluids are NH₃-H₂O and H₂O-LiBr, it is observed that the disadvantages associated with these working fluids have prompted researchers, to search for alternate working fluids. Though R22-organic solvent based absorption refrigeration systems have been extensively studied by Fatouh et al. (1994), Karthikeyan et al. (1995) and Sujatha et al. (1997), HCFCs along with CFCs, are also covered by Montreal and other International Protocols and are being phased out. Alternatively, R134a based VARS are being investigated. Nezu et al. (2002) and Yokozeki (2005) investigated R134a as a refrigerant in VARS with various absorbent combinations and concluded that R134a-Dimethyl acetamide (DMA) and R134a-DMF are promising for the absorption refrigeration system than other R134a-absorbent combinations. It is also found that the circulation ratio is lower and COP is higher for R134a-DMF system compared to R134a-DMA system. Mani (2009) carried out experimental studies on compact VARS system with plate heat exchangers and reported that this system could be very competitive for applications ranging from -10°C to 10°C, with heat source temperature in the range of 75°C to 90°C.

Generator is considered as one of the crucial components in the vapour absorption refrigeration system. Boiling process in generator is characterized by simultaneous heat and mass transfer phenomena. Use of plate heat exchanger as the system components of VARS has increased due to its high heat transfer efficiency, high heat transfer area to volume ratio, etc. Various authors (Kang et al. 1998; Lee et al. 2002 and Jesus Cerezo et al. 2009) have used plate heat exchanger as absorber and investigated its performance on VARS systems. Roriz et al. (2004)
used the plate heat exchanger as generator and compared the performance of compact generator with that of a falling film desorber with ammonia-water mixture and proved the feasibility of compact generator. Taboas et al. (2010) have measured heat transfer coefficient and pressure drop for ammonia-water combination under flow boiling conditions in a vertical brazed plate heat exchanger, at different operating conditions. Yan and Lin (1999) carried out experiments on evaporation, to measure heat transfer coefficient and pressure drop for R134a flowing in a plate heat exchanger. Contrary to the mass flux effects, the heat flux did not show significant effects on the heat transfer at high quality, but it showed some influence at low quality. Based on their experimental data, correlation equations have been developed for heat transfer coefficient and friction factor. Experimental data of Taboas et al. (2010) on flow boiling of ammonia-water in a plate heat exchanger are compared by Taboas et al. (2012) with the values predicted using the correlations available in the open literature for the boiling heat transfer coefficient and pressure drop. A new correlation has also been proposed based on a separate model to obtain the boiling heat transfer coefficient. Review of literature revealed that a comprehensive study on heat and mass transfer of compact generator using R134a-DMF is yet to be investigated. The present investigation is focused on heat and mass transfer on plate heat exchanger used as generator in a 1 kW capacity VARS using R134a-DMF.

2. EXPERIMENTAL SETUP

Schematic diagram of the vapour absorption refrigeration system is shown in Fig.1. The setup consists of brazed plate heat exchangers used as generator, condenser, evaporator, absorber and solution heat exchanger.

![Schematic diagram of R134a-DMF based VARS with plate heat exchangers](Balamurugan and Mani, 2012a)
Experimental facility also contains a solution pump, cooling water source, hot water source, cooling load simulator, instrumentation and valves. Refrigerant loop starts from the gas separator where the R134a vapour generated in the compact generator is separated and is allowed to get condensed in the condenser and stored in the receiver. Cooling water source is used to remove heat of condensation. Liquid R134a collected in the receiver is expanded through throttle valve and evaporated in the evaporator. Chilled water from the simulator is used to give the cooling load. R134a vapour from the evaporator is absorbed by the weak DMF solution in the absorber, which marks the beginning of the solution loop. Heat of mixing is removed by water from cooling water source. A diaphragm type reciprocating pump is used to pump the strong solution collected in the absorber tank through solution heat exchanger and solution preheater to compact generator. Figure 2 shows the compact generator, used for the present study, which is a plate heat exchanger with Chevron-H type plate channels. Hot water from the heat source is supplied to generator in counter flow direction. After desorption, the two phase mixture from the generator is sent to gas separator. Weak solution remaining in the phase separator is sent to the absorber through solution heat exchanger and pressure reducing valve.

Hot water source consists of an insulated hot water tank, electric heaters, pump, flow meter, PT100 sensor, PID temperature controller, contactor, piping and valves. Cooling water source consists of R22 based vapour compression refrigeration (VCR) circuit, insulated cooling water tank, electric heaters, pump, flow meter, PT100 sensor, PID temperature controller, contactor, piping and valves. Cooling load simulator features an insulated chilled water tank, electric heaters, pump, flow meter, PT100 sensor, PID temperature controller, contactor, piping and valves. It is used to supply water as cooling load to evaporator and maintains a constant desired value of chilled water temperature at evaporator inlet.

Location of various temperature sensors, pressure sensors, flow meters, online density meter and valves are indicated in Fig. 1. All these measuring instruments have been calibrated. Copper-constantan thermocouples are used as temperature sensors, to measure temperature at prominent locations, with a maximum measurement uncertainty of ± 0.5 °C. Piezo-electric type pressure transducers are used as pressure sensors with a measurement uncertainty up to ± 4.55 %. Metal tube rotameters are used to measure flow of liquid refrigerant, weak solution and hot water with a measurement uncertainty up to ± 5 %. Glass rotameters are used to measure flow of cooling water and chilled water with a measurement uncertainty up to ± 2.5 %. An online density meter is used to measure density of strong and weak solutions with a measurement uncertainty of ± 0.3 %.

Figure 2: Schematic diagram of compact generator (Balamurugan and Mani, 2012a)
Figure 3: Experimental facility of VARS with compact generator (Balamurugan and Mani, 2012b)

Concentrations of strong and weak solutions are evaluated from the measured density values using HBT (Hankinson-Brobst-Thomson) equation used by Reid et al. (1989) in their book. Data acquisition system connected to a computer is used to monitor and record the readings from all these instruments and sensors. Photograph of the experimental facility is shown in Fig. 3.
3. EXPERIMENTAL PROCEDURE

Generally, when not in operation, refrigerant and solution loops are disconnected by closing the valve between i) gas separator and condenser and ii) evaporator and absorber. Initially, hot water thermostat and cooling water thermostat are started. Hot water is circulated through the generator at a temperature higher than that to be maintained in the generator. Cooling water is circulated through the condenser and the absorber in series circuit. Cooling load simulator is operated by circulating water through the evaporator. Water temperature in the chilled water tank is maintained constant by switching on heaters equivalent to cooling capacity of system. Solution pump is then started to circulate strong solution through generator. Level of weak solution collected in the gas separator, level of strong solution in the absorber storage tank and pressure at salient locations of solution loop are monitored continuously. When pressure in the gas separator becomes greater than that in condenser, the valve between them is opened to allow refrigerant vapour to get condensed in condenser. The condensed liquid refrigerant is collected in the receiver and its level is monitored continuously. When sufficient amount of refrigerant is stored, the valve between evaporator and absorber is opened and the liquid refrigerant is allowed though expansion devices to evaporator from where the refrigerant vapour is sent to absorber. Flow rates of weak solution and liquid refrigerant are regulated to maintain steady flow in the system. System is run continuously by monitoring pressure transducer, thermocouple, flow meter and level gauge readings at various locations. When all these readings remain constant over a time period, it is presumed that system has attained steady state operating conditions and all these readings are recorded in the computer. Water flow rates in the hot water thermostat, cooling water thermostat and cooling load simulator are maintained constant at the design value. Experimental tests are repeated for different operating conditions. While shutting down the system after experimentation, solution loop and refrigerant loop are isolated by closing the valve between the evaporator and absorber and then closing the valve between the gas separator and condenser.

4. RESULTS AND DISCUSSION

Experimentation has been carried out on compact generator of VARS with a cooling capacity of 1kW by varying the operating parameters viz., liquid refrigerant flow rate from 0.002 to 0.015 m$^3$/hr$^{-1}$, solution flow rate from 0.02 to 0.05 m$^3$/hr$^{-1}$, hot water temperature from 85 to 97°C, cooling water temperature from 15 to 30°C. Parametric studies were carried out from the following range of operating parameters: Generator temperature: 80-95°C, Generator pressure: 600-1000 kPa, Solution initial concentration: 0.59-0.75 kg/kg. Cooling water has been supplied to absorber and condenser in series arrangement as shown in Fig. 1. In every run of the experiment, system is allowed till it attains steady state condition, when the performance of compact generator is determined. Influence of solution flow rate, generator temperature and pressure on desorption in compact generator is presented.

4.1 Effect of generator temperature

Figure 4 shows effect of flow rate of strong solution and generator temperature on heat transfer coefficient and mass transfer coefficient during desorption process. As the refrigerant content in solution increases with flow rate, more heat is utilized at higher desorption rates.
Heat transfer rate also increases with increase in generator temperature resulting in increased desorption of R134a vapour. Thus, increase in heat transfer rate and mass transfer rate results in the increase in heat and mass transfer coefficients with flow rate and generator temperature.

Variation of heat transfer rate and desorption rate with respect to solution flow rate at different generator temperatures are shown in Fig. 5. Heat and mass transfer coefficients increases with increase in flow rates and generator temperatures, for the reasons explained above. Effect of solution flow rate on quality of refrigerant vapour at the exit of generator and overall heat transfer coefficient, at different generator temperatures, is shown in Fig. 6. Exit quality and overall heat transfer coefficient increase with the increase in solution flow rate and generator temperature. At higher generator and flow rates, heat transfer coefficient and mass transfer coefficient increase, for the reasons explained above, resulting in increase in generation of R134a vapour. This increases the exit refrigerant vapour quality and overall heat transfer coefficient, with solution flow rate and generator temperature. As the solution exists as two phase mixture, lower quality is measured at the exit of generator, as shown in the figure. But this quality is improved by using gas separator after generator and obtained between 97.49 and 99.84 % which is contributed by refrigerant (R134a) vapour alone with very little traces of liquid absorbent.

Effect of generator performance on the performance of the vapour absorption system with respect to generator temperature is shown in Figs. 7 and 8. As the desorption rate increases with generator temperature, concentration difference between entry and exit of generator also increases. This requires the compact generator to use only less amount of solution for desorption process to generate unit mass of refrigerant vapour, for the same operating conditions. Hence, lesser circulation ratio is required at higher generator temperatures as shown in Fig. 8. Because of lower circulation ratio, requirement of heat flux imposed on the generator will also be lower, resulting in higher COP for the system, at higher generator temperatures.
4.2 Effect of generator pressure

Effect of generator pressure on heat transfer coefficient and mass transfer coefficient is depicted in Fig. 9. At a given generator temperature and solution flow rate, with decrease in generator pressure, there exists a high temperature gradient between the hot water and the solution, due to the solution entering the generator at a lower equilibrium temperature. Hence the heat transfer rate increases as the generator pressure decreases, resulting in enhanced mass generation rate of R134a vapour. Hence increased heat and mass transfer rates result in increased heat transfer coefficient and mass transfer coefficient respectively, with decrease in generator pressure. Variation of heat transfer coefficient and mass transfer coefficient with respect to solution flow rate is already explained earlier in Fig. 4.

![Figure 9: Effect of generator pressure on heat and mass transfer coefficients](image1)

![Figure 10: Effect of generator pressure on heat transfer rate and desorption rate](image2)

Figure 10 shows the variation of heat transfer rate and desorption rate with generator pressure. As the heat and mass transfer coefficients increase, heat transfer rate and desorption rate also increase at lower generator pressure and at higher solution flow rate respectively. Figure 11 shows the role of generator pressure on the performance of vapour absorption refrigeration system. With the increase in generator pressure, desorption rate decreases, for the reasons explained above, resulting in decrease in the concentration difference of the solution. Figure 12, thus, reveals that higher flow rate of strong solution is required by the generator to desorb unit mass of refrigerant vapour, resulting in increase in the circulation ratio at higher generator pressures. Consequently, more amount of heat input is required to be supplied to the generator for higher circulation ratio, resulting in lower COPs at higher generator pressures, as shown in Fig. 13.

![Figure 11: Effect of generator pressure on concentration difference across generator](image3)

![Figure 12: Effect of generator pressure on circulation ratio](image4)
Experimental investigations have been carried out on a 1 kW capacity vapour absorption refrigeration system to study heat and mass transfer during desorption process taking place in compact generator. R134a-DMF is used as working fluid. Average heat transfer coefficient, volumetric mass transfer coefficient, heat transfer rate, desorption rate, quality of refrigerant vapour, circulation ratio and COP of the system have been determined from the experiments. Effect of important operational parameters viz., solution flow rate, generator temperature and generator pressure on the performance of generator and VARS is studied. Results showed that heat and mass transfer coefficients, heat transfer rate and desorption rate increase with solution flow rate and generator temperature but decrease with increase in generator pressure. Increase in generator temperature and decrease in generator pressure requires less circulation ratio of solution and hence give better system COP.

**5. CONCLUSIONS**

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Subscripts</th>
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<tbody>
<tr>
<td>A</td>
<td>heat transfer area</td>
<td>(m²)</td>
<td></td>
</tr>
<tr>
<td>Cp</td>
<td>specific heat</td>
<td>(Jkg⁻¹K⁻¹)</td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>circulation ratio</td>
<td>(-)</td>
<td></td>
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<tr>
<td>Hₑᵥₐ</td>
<td>latent heat of vaporization</td>
<td>(Jkg⁻¹)</td>
<td></td>
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<tr>
<td>h</td>
<td>heat transfer coefficient</td>
<td>(Wm⁻²K⁻¹)</td>
<td></td>
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<tr>
<td>k</td>
<td>thermal conductivity</td>
<td>(Wm⁻¹K⁻¹)</td>
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<tr>
<td>LMCD</td>
<td>log mean concentration difference</td>
<td>(kgkg⁻¹)</td>
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<tr>
<td>LMTD</td>
<td>log mean temperature difference</td>
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<tr>
<td>m</td>
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<tr>
<td>M</td>
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<tr>
<td>Q</td>
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<td>(W)</td>
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<tr>
<td>T</td>
<td>Temperature</td>
<td>(°C)</td>
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<tr>
<td>t</td>
<td>plate thickness</td>
<td>(m)</td>
<td></td>
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<tr>
<td>U</td>
<td>overall heat transfer coefficient</td>
<td>(Wm⁻²K⁻¹)</td>
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<tr>
<td>V</td>
<td>channel volume</td>
<td>(m³)</td>
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<tr>
<td>x</td>
<td>vapour quality</td>
<td>(-)</td>
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<tr>
<td>X</td>
<td>liquid concentration</td>
<td>(kgkg⁻¹)</td>
<td></td>
</tr>
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</table>
REFERENCES

8. Mani, A., 2009, Studies on compact bubble absorber of the vapour absorption refrigeration system, A report to Department of Science and Technology, Government of India.

APPENDIX

\[ Q = m_{pw} C_p T (T_{hw,i} - T_{hw,o}) \]  \hspace{1cm} (1) \hspace{1cm} \text{LMTD} = \frac{(T_{hw,i} - T_{s,o}) - (T_{hw,o} - T_{s,i})}{\ln \left( \frac{T_{hw,i} - T_{s,o}}{T_{hw,o} - T_{s,i}} \right)} \]  \hspace{1cm} (2) \hspace{1cm} U = \frac{Q}{(A) (\text{LMTD})} \]  \hspace{1cm} (3) \hspace{1cm} \text{h_{avg}} = \left( \frac{1}{U} - \frac{1}{h_{hw}} - \frac{t}{k_{wall}} \right)^{-1} \]  \hspace{1cm} (4)
\[
M = \frac{m_d}{(V) \text{ (LMCD)}} \quad \text{(5)}
\]

\[
\text{LMCD} = \frac{(X_{eq,i} - X_{s,i}) - (X_{s,o} - X_{eq,o})}{\ln \left( \frac{X_{eq,i} - X_{s,i}}{X_{s,o} - X_{eq,o}} \right)} \quad \text{(6)}
\]

\[
Q_{ph} = Q_{ph,sens} + Q_{ph,lat} \quad \text{(7)}
\]

\[
Q_{ph,lat} = m_x H_{fg} x_{ph,o} \quad \text{(8)}
\]

\[
x_{ph,o} = \left( \frac{1}{m_x H_{fg}} \right) \left( Q_{ph} - Q_{ph,sens} \right) = x_{gen,i} \quad \text{(9)}
\]

\[
x_{gen,o} = x_{gen,i} + \left( \frac{Q_{gen}}{m_x H_{fg}} \right) \quad \text{(10)}
\]

\[
\text{CR} = \frac{m_x}{m_d} \quad \text{(11)}
\]

\[
\text{COP} = \frac{Q_{evap}}{Q_{gen}} \quad \text{(12)}
\]