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BASIC STUDY ON THE OIL RECOVERY IN A HYBRID HEAT PUMP USING AMMONIA/WATER SOLUTION

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ABSTRACT

In an ammonia/water hybrid heat pump system which is a vapor compression cycle with a solution circuit, lubricating oil is commonly used for the compressor. Since Poly-Alpha-Olefin (PAO) oil which is commonly used for ammonia is immiscible with the ammonia/water solution, a proper oil recovery method is required for a smooth operation of the compressor. Although the oil separator installed at the outlet of the compressor removes most of the oil from the refrigerant vapor, some oil droplets are carried over and accumulated in the solution reservoir. Unlike the pure ammonia vapor compression system, the density of PAO oil is smaller than that of ammonia/water mixture which has the ammonia concentration of 30-40%, and the oil tends to rise and gather near the liquid/vapor interface.

In this study, a method for oil recovery from the solution reservoir is suggested. In the present method, the mixture of the oil and the solution is drained into an oil separator having a narrow cylinder at the top, if the oil in the reservoir is greater than a certain amount. The oil droplets in the solution rise by buoyancy and gather at this upper narrow cylinder. The gathered oil is extracted and returned to the compressor by an oil recovery pump. Since the solution has to be returned to the reservoir as soon as the separation process is finished, the process time for the separation should be as short as possible. To predict the time for the separation, experiments and simulations have been carried out. The model using the multiphase segregated flow (MSF) showed that a proper choice of droplet diameter is necessary to predict a correct separation time. Also, a simulation model which is able to consider the effect of surface tension and droplet merging is needed to be developed.

INTRODUCTION

In general, lubricating oil is necessary for compressors of vapour compression refrigeration and heat pump systems. With the refrigerant flow, some of immiscible oil escape from the compressor as droplets and accumulates in other components than the compressor. Although there are various methods, it is hard to recover the oil completely. If a substantial amount of the lubricating oil is not recovered, it causes a couple of serious problems**.** A lack of lubricating oil in the compressor leads to a drop of the performance or a failure of the system [1]. Another problem is that the oil accumulated in the heat exchanger reduces the heat transfer performance [2].

NOMENCLATURE

α	[-]	Volume fraction
ρ	[kg/m^3]	Density
μ	[Pa·s]	Viscosity
$\mathbf{v}$	[m/s]	Velocity
$\mathbf{v}_r$	[m/s]	Relative velocity
p	[N/m^2]	Pressure
$\mathbf{g}$	[m/s^2]	Gravity
$\mathbf{M}$	[kg·m/s]	Inter-phase momentum
A_{ij}^D	[-]	Linearized drag coefficient
C_D	[-]	Cartesian axis direction
l_{cd}	[m]	Diameter of droplet

Dimensionless numbers

We	[-]	Weber number, $u_t{}^2 d_p \rho_c/\sigma$
Re	[-]	Reynolds number, $u_t d_p \rho_c/\mu_c$

Subscripts

I	Phase *i*
J	Phase *j*
C	Continuous phase
D	Dispersed phase

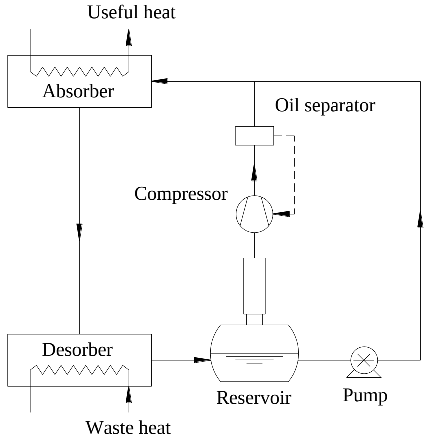


Figure 1 Schematic diagram of a hybrid heat pump

The ammonia/water hybrid heat pump system in this study (Figure 1) is basically a vapour compression cycle with a solution circuit. The system has a function to deliver the useful heat at high temperature level by recovering the waste heat. Because of the temperature glide in the absorber and desorber, higher temperature can be obtained compared to a simple vapour compression heat pump. In this ammonia/water hybrid heat pump system, similar problems can occur due to insufficient oil recovery. Poly-Alpha-Olefin (PAO) lubricating oil which is used for an ammonia/water hybrid heat pump system is immiscible with ammonia/water solution. Although the oil separator installed at the outlet of the compressor removes most of the oil from the refrigerant vapour, some oil droplets are carried over and accumulated in the solution reservoir.

Therefore, a method for oil recovery from the solution reservoir is suggested in this study. In the present method, the mixture of the oil and the solution is drained into an oil separator having a narrow cylinder at the top, if the oil in the reservoir is greater than a certain amount. The oil droplets in the solution rise by buoyancy and gather at this upper narrow cylinder. The separated oil at the top is extracted and returned to a compressor, and the remaining solution is returned to the reservoir.

Since the solution has to be returned to the reservoir as soon as the separation process is finished, the process time for the separation should be as short as possible. To predict the time for the separation, experiments and simulations have been carried out.

WORKING PRINCIPLE

The principle of the oil separation in the present study is to use the density difference between the oil and ammonia/water solution. Figure 2 shows the density of PAO oil and ammonia mixture with the concentration of 30-40%. The density of pure ammonia liquid is lower than that of PAO oil. However, the 30-40% ammonia aqueous solution has a higher density than PAO oil. The density difference between the solution and oil increases as the concentration of ammonia aqueous solution becomes lower. The density difference for a given ammonia concentration does not change much with the temperature.

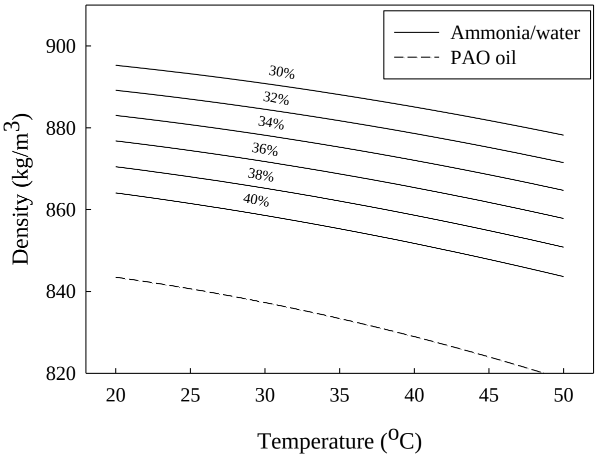
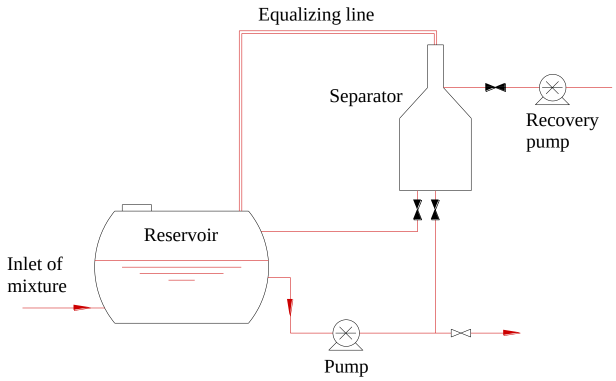
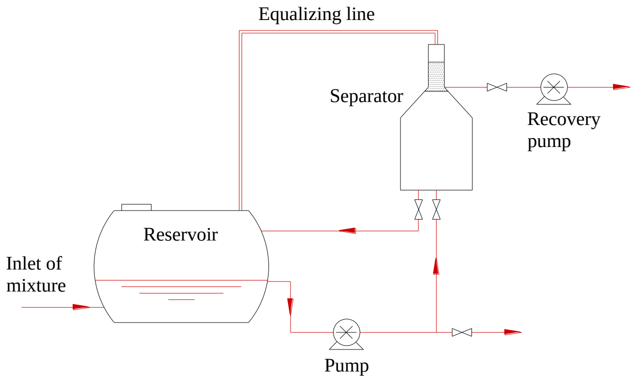


Figure 2 Density of ammonia/water and PAO oil as a function of ammonia concentration and temperature



(a) Normal operation mode



(b) Oil-recovery operation mode

Figure 3 Two modes of operation

Because of the density difference, the PAO oil rises by buoyancy and builds a thin layer at the top of the reservoir as shown in Figure 3 (a). If the amount of oil in the reservoir exceeds a certain value, the oil recovery mode is started. In the oil recovery mode, the valve to the oil separator is opened and some of the solution containing the PAO oil flows into the oil separator. If the solution entirely fills the separator, the inlet valve is closed. Since the oil separator has a narrow neck at the top, the oil is mainly collected in the neck as the thickness of the oil layer increases. Then the collected oil is returned to the compressor by an oil recovery pump, and the solution is returned to the reservoir by opening the exit valve.

EXPERIMENT

Figure 3 shows the schematics of the experimental setup which is composed of a reservoir, a separator, a pump, and valves.

The preliminary experiments were performed using oil and water instead of ammonia/water solution, since the basic mechanism is the same for both mixtures. To observe the oil thickness, the separator is made of transparent acryl (Figure 4). The diameter of the neck is 1/9 of the bottom cylinder. To extract the oil at a proper position, four extraction valves have been installed at the neck.

The experimental process starts with filling of PAO oil into the water in the reservoir. The volume fraction of oil was 0.18%. Then the mixture is well mixed while heating it to a given temperature (40^{o}C). When the experimental condition is reached, the separator is entirely filled with the mixture is by the pump. As time passes, the thickness of the oil collected at the neck was measured and the volume fraction of the collected oil was calculated.

The properties of water and the PAO oil (Gargoyle Arctic SHC 230, Exxon Mobil) are given in Table 1.

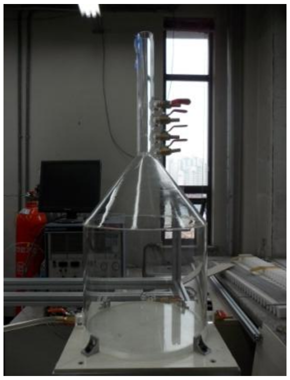


Figure 4 Oil separator

Table 1 Physical properties of the liquids (40℃)

Experiment liquids	Density ρ ($\mathrm{kg/m^3}$)	Viscosity μ ($\mathrm{mPa \cdot s}$)
Water	992.2	0.6533
Oil	831	182.8

EXPERIMENTAL RESULT

Figure 5 shows the thickness and the volume fraction of the collected oil at the neck. Analyzing the data, the accumulation process of is found to be divided into three steps. In the first stage (up to ~ 50 seconds), the oil droplets in a cylinder with a height of the entire separator and the circular cross sectional area of the neck rise and gathered at the neck. In the second stage (50 to 150 seconds), the oil droplets which are not in this cylinder volume rise, contact the cone surface, decelerate, and merge with each other. In this stage the oil is collected quite slowly. In the third stage, the droplets start to leave the cone surface, and the oil collection rate is increased again. In about 20 minutes, almost all oil droplets are collected at the neck.

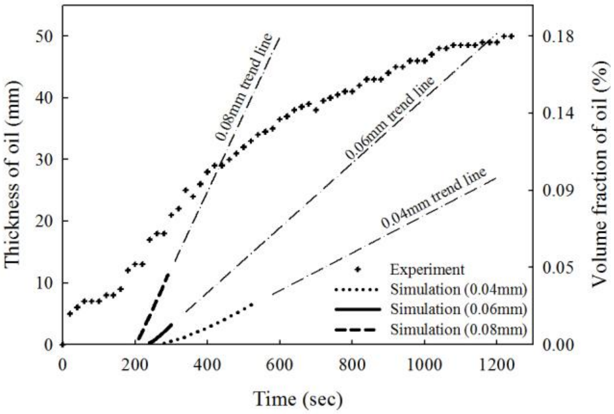


Figure 5 Experimental results compared with simulation

NUMERICAL SIMULATION

To predict the time for oil separation at different conditions, a model using the multiphase segregated flow (MSF) was applied. The MSF model which solves set of continuity and momentum equations for the whole phases is useful in simulations such as bubbles or droplets in continuous fluid.

To simulate the motion of a dispersed phase (droplet) in a continuous phase, a definition of drag coefficient is important. Typically, a droplet is a spherical shape in low *We* numbers. The velocity of a droplet is influenced by the diameter of a droplet, and the drag coefficient is calculated from the velocity of droplet [3,4].

Clift, R. et al. purposed a correlation as a function of Reynolds number. Since this correlation was thought be suitable for our purpose, it was used in the present simulation [5].

Multiphase segregated flow model solves continuity equation (1) and momentum equation (2) for each phase. This model assumes that the pressure is same in all phase.

$$\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla\cdot(\alpha_i\rho_i\mathbf{v}_i) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\alpha_i\rho_i\mathbf{v}_i) + \nabla\cdot(\alpha_i\rho_i\mathbf{v}_i\mathbf{v}_i) = -\alpha_i\nabla\mathrm{p} + \alpha_i\rho_i\mathbf{g} + \mathbf{M}_i \quad (2)$$

where α_i is the volume fraction which takes from 0 to 1, ρ is the density, $\mathbf{v}$ is the velocity, p is the pressure and $\mathbf{M}_i$ is the inter-phase momentum transfer per unit volume. Inter-phase momentum $\mathbf{M}_i$ is defined by equation (3), and only the drag force is considered.

$$\mathbf{M}_i = \sum_j \mathrm{A}_{ij}^{\mathrm{D}}\left(\mathbf{v}_j - \mathbf{v}_i\right) \quad (3)$$

The linearized drag coefficient $\mathrm{A}_{ij}^{\mathrm{D}}$ can be calculated by equation (4). The definition of the drag coefficient which is given by Clift, R. correlation (5) is used.

$$\mathrm{A}_{ij}^{\mathrm{D}} = \frac{3}{4}\frac{\alpha_d(\alpha_c)^{n_v}\rho_c \mathrm{C}_{\mathrm{D}}}{l_{\mathrm{cd}}}|\mathbf{v}_{\mathrm{r}}| \quad (4)$$

$$\mathrm{C}_{\mathrm{D}} = \begin{cases} \frac{24}{\mathrm{Re}_d}\left(1 + 0.15 Re_d^{\ 0.687}\right) ; 0 < Re_d \leq 1000 \\ 0.44 \qquad ; \ Re_d > 1000 \end{cases} \quad (5)$$

The subscripts c and d are used for a representation of continuous phase and dispersed phase. l_{cd} is the diameter of dispersed phase such as droplet, and $|\mathbf{v}_{\mathrm{r}}|$ is the relative velocity between the phases.

The separator geometry is axisymmetric and the flow in the separator is assumed to be laminar. All boundary conditions are wall which is no-slip condition except axis. Implicit unsteady state method is carried out to determine the variation of oil thickness at the neck with time.

The initial condition of the volume fraction of the oil was 0.18%, and each velocity of water and oil was zero. It is assumed that the oil droplets which have a given diameter (0.04mm, 0.06mm, 0.08mm) are distributed homogeneously in the continuous phase (water) initially.

The calculation meshes are created using software ANSA v12 with mixed-grid type (tria-quad), and meshes of about 75,000 are used (Figure 6). The simulation was carried out with a commercial tool, STAR-CCM+ v5.

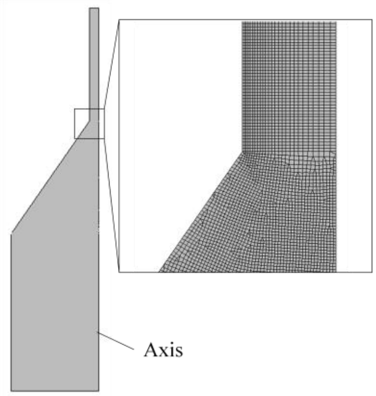


Figure 6 Computational mesh for the oil separator

SIMULATION RESULTS

In Figure 5, the simulation data are compared with the experimental ones. Because of the required calculation time, simulations were carried out not to 1200 seconds, but to the time when the increase rate of the oil thickness shows a certain gradient. Then, the estimation lines were linearly extrapolated.

During about 300 seconds from the simulation start, the oil layer was scarcely built at the neck. Then, the oil thickness increased almost linearly. As expected, the oil thickness was found to increase more slowly as the droplet size decreases. The gradient of the line for a droplet diameter of 0.04 mm was found to be similar to the experimental one. However, in estimating the total separation time, the line for 0.06 mm diameter showed a best result.

CONCLUSION

For an ammonia/water hybrid heat pump system, a method for oil recovery from the solution reservoir was suggested. The working principle using the density difference of two immiscible liquids was verified by the experiments. In the preliminary experiment using pure water and PAO oil, it was found that almost all oil droplets were collected at the neck in about 20 minutes.

Numerical simulations using the multiphase segregated flow (MSF) model have been also carried out. The simulation results showed that a proper choice of droplet diameter is necessary to predict a correct separation time. The droplet diameter of 0.04 - 0.06 mm was found to exhibit a close result to the experimental one. To estimate the separation time more accurately, a simulation model which is able to consider the effect of surface tension and droplet merging is required.

REFERENCES

[1] Mohammed Youbi-Idrissi, and Jocelyn Bonjour, The effect of oil in refrigeration: Current research issues and critical review of thermodynamic aspects, *International Journal of Refrigeration*, Vol. 31, 2008, pp. 165-179

[2] Kenneth N. Marsh, and Mohamed E. Kandil, Review of thermodynamic properties of refrigerants - lubricant oil, *Fluid Phase Equilibria*, Vol. 199, 2002, pp. 319-334

[3] K. Bäumler, M. Wegener, A.R. Paschedag, and E. Bänsch, Drop rise velocities and fluid dynamic behavior in standard test systems for liquid/liquid extraction-experimental and numerical investigations, *Chemical Engineering Science*, Vol. 66, 2011, pp. 426-439

[4] G.P. Lucas, and N. Panagiotopoulos, Oil volume fraction and velocity profiles in vertical, bubbly oil-in-water flows, *Flow Measurement and Instrumentation*, Vol. 20, 2009, pp. 127-135

[5] Clift, R., Grace, J.R., and Weber, M.R., Bubbles, Drops and Particles, *Academic Press*, 1978