Controllable Cycle Investigation of Direct Fired Absorption Heat Pump for Residential Heating Systems

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ABSTRACT

A prototype of a monovalent air-to-water absorption heat pump is developed with a heating capacity rating of 25 kW for residential heating systems. The ambient air supplies the external energy, and the driving energy comes from a two-stage adjustable oil burner. As the temperature of the outside air rises, residential heating requirements drop, but the output heat of the heat pump remains constant. Therefore heat pumps have to turn on and off in fixed-cycles. The intermittent losses caused by the fixed-cycle operation of conventional absorption heat pumps have been avoided by a new, patented operating method. This makes this absorption heat pump particularly suitable for use in residential heating systems. Based on this system we developed a procedure that makes a controllable cycle possible for a sorption heat pump, which is suited to actual heating requirements without fixed-cycles. The significant improvement is the possibility of year-round operation in heat pump mode, whereby ambient heat can be fed to the evaporator even when the outside air temperatures are below - 3 ºC and the sorption heat pump can operate at his optimal COP. This will be achieved by the control of the concentration of the ammonia-water solution and by the adjustment of an infinitely variable burner. For the generator of this sorption heat pump the heat and mass transfer phenomenon had to be investigated.

KEY WORDS
Absorption heat pump, direct fired, ammonia, controllable cycle, residential heating system.

DESCRIPTION OF THE ABSORPTION HEAT PUMP WITH FIXED-CYCLE

Residential heating systems have special requirements to air-to-water heat pumps. While the ambient air temperature is dropping, the residential heating consumption rises. In addition the temperature of the heating water has to be raised according to the demands of the heating system. For optimization of the COP for this application, the highest possible concentration of ammonia was chosen for the non-controlled absorption heat pump. The concentration of the strong ammonia solution is determined by the temperature of heating water and the corresponding temperature of the ambient air, at which the refrigerant just barely evaporates. This limiting value of ambient air temperature is -3 ºC in the prototype with an air impinged evaporator which was developed and tested at our institute [1, 2, 3].

Below this ambient air temperature the absorption heat pump changes into a so-called internal boiler mode. That means the ammonia vapor flows from the rectifier directly to the absorber. The two-stage fuel oil burner switches to a higher capacity, and the mass flow of the weak ammonia solution that has risen accordingly runs over an additional throttle. Thereby the high pressure is maintained. Thus the requirements of the heating system are met even when the ambient air temperature drops below -3 ºC without any input of ambient heat.

In order to meet the heat demand of a 25 kW house this monovalent heat pump works above a temperature of ambient air at -3 ºC with a burner capacity of about 9.4 kW in the heat pump mode. It yields a heating capacity of about 15 kW nearly constant in the complete outside temperature range. In the so-called internal boiler mode, which works at an ambient air temperature below -3 ºC, the two-stage burner switches to a capacity of 23.5 kW, whereby the heating capacity of the absorption heat pump is raised to 25 kW by a condensing flue gas heat exchanger.

While the residential heating requirement rises linearly with a decrease in ambient air temperature, the absorption heat pump offers a nearly constant heating capacity in the respective range of ambient air temperature. In order to compensate for this discrepancy between the heat producer and the heat consumer, a load water buffer with a volume of 145 l is installed parallel to the heating loop that consists of a mixing valve, radiators and a load pump. When the temperature of the heating water at the bottom of the buffer reaches a maximum value, the absorption heat pump switches off. The heating cycle is fed by the load water buffer until the temperature of the heating water at the top of the buffer reaches a minimum value.

When the heat pump switches off in this described fixed-cycle operation, in both operating modes all valves (V1 to V5) get

closed (fig. 1). The burner, the solution pump and the fan are switched off. Because no heat is delivered, the available heat capacity in the generator causes an increase in the high pressure. When a maximum value is reached, the valve V2 opens for a brief moment until the high pressure has dropped to the operating state. During this process the condenser is fed with a small quantity of refrigerant. Because in this operating mode the state variables of the solution in the generator (pressure, temperature, concentration) remain nearly constant, the steady state of the absorption heat pump process is briefly reached again after the heat pump switches on once more [4].

DEVELOPMENT AND INVESTIGATION OF GENERATOR OPERATION

Taking up the suggestions of Altenkirch [5] concerning an approximation to the reversibility of the heat transfer between the strong ammonia and the weak ammonia solution, this absorption heat pump is suited for a configuration of the heat transfer within the generator and the rectifier. While in this process the concentration of the ammonia strong solution is kept constant, the concentration of the weak solution is lowered to a value that such an external solution heat exchanger is not necessary. When the generator contains such an internal direct heat transfer and when the solution in the generator has a distinct near linear temperature profile with a solution concentration gradient, a higher rectification of the rising vapor is reached by the incoming strong solution. The specific vapor mass flow rises.

Using the equations of state by Ziegler [6], this process was investigated with a computing program (fig. 2). Under the state of equilibrium between the strong ammonia solution and the vapor at the generator head, the expected increase in COP makes itself evident with a drop in concentration of the weak ammonia solution. The concentration of the strong ammonia solution was kept constant at 38%. The lower the temperature difference between weak and strong solution at the generator head is, the more the COP rises. These processes produce a rise of the specific vapor mass flow. The transferred heat flux of the internal solution heat exchanger drops with rising concentration difference between the departing weak and the incoming strong ammonia solution. The reason for this is mainly the simultaneous drop of the mass flow of the weak ammonia solution.

The solution zone of the generator is set in an annular gap around the combustion chamber. The heat pump is directly fired by a soot-free blue burner, and the heat is transferred from the inside as well as from the outside to the solution zone. In the solution zone there is a spiral tube for the weak ammonia solution , and the solution zone is filled with Raschig rings (fig. 3b). In the rectifier there is also a heat transfer between the weak and the strong solution . This heat transfer between the weak and the strong ammonia solution on the one side and between the vapor and the strong solution on the other side is performed in such a way that the strong ammonia solution enters at the generator head with a maximum undercooling of about 10 K. The vapor concentration is in equilibrium with the incoming strong ammonia solution. The temperature profile measured in the solution zone runs nearly linear in altitude and only has a deviance at the transition point from the heated to the unheated zone. In this area there is a backmixing effect (fig. 3a). The backmixing of the fluid phase is defined by. Eq.2.

The strong ammonia solution enters the rectifier at 37 °C, is heated to a temperature of 95.6 °C by the weak ammonia solution and vapor and then enters the generator head. There the strong ammonia solution has a pressure of 14.4 bar and is

undercooled by 6 K. The strong ammonia solution flows in counterflow to the rising ammonia vapor bubbles to the bottom the generator and is reduced to a concentration of 15.5 %. Ther has a temperature of 152.2 °C . It leaves the generator through internal solution heat exchanger with a temperature of 107.4 °C a cools in the rectifier in a counterflow to the strong ammo solution of 51.6° C.

In the ideal generator process the strong ammonia soluti flows into the generator in a saturated state, and its concentrati drops due to vapor generation on the way to the bottom of generator. The vapor in this process is in thermodynam equilibrium with the solution at every location in the solution zon For this reason there is a build-up of a concentration profile anc temperature profile in both phases in the generator. In the id generator process the incoming strong ammonia solution, departing weak ammonia solution and the emerging vapor are ir state of equilibrium at the generator head. In comparison to r generator processes, the vapor has a maximum amount of ammon and the rectifier capacity is minimal. The ideal generator proc requires that the coupled transport of energy and mass runs id between the phases and also, that in both phases diffusion currer of the mass components do not appear.

In the real generator process, a convective diffusion in t fluid phase is caused by the relative motion of both phases. On t one hand the rising vapor bubbles carry adhering fluid upwards. C the other hand behind the bubbles there is fluid transported traction. This process is overlayed by a convective flow. For reaso of continuity, for each mass of fluid being carried upwards there h to be another one being carried downwards at a different locatio There is a downward motion of ammonia caused by this circulati movement in the fluid phase, and simultaneously a movement water in the opposite direction. By this axial backmixing, t concentration gradient in the solution zone is decreased. At t same time the axial backmixing in the fluid phase causes a decrea of the temperature gradient in the generator. Under unfavourat conditions the ammonia concentration of the solution at t generator head approximates the weak ammonia solution at t generator bottom. The solution temperature at the generator he rises. For this reason the solution temperature and the solutic concentration at the generator head are different from the state the incoming saturated solution . A jump in temperature ar concentration at the fluid level follows [7].

In generator processes with backmixing, the outgoing vap has a lower concentration of ammonia and a higher temperatur Thereby in the real generator process the rectifier capacity rises i comparison to the ideal process. A further consequence of the axi backmixing is a rise in temperature in the outgoing weak ammon solution. The consequence of this is a rise of the specific generat capacity and an increase in the required reflux ratio of the rectifie This is seen in the following definition of the process COP ζ_P the cycle.

$$\zeta_P = 1 + \frac{1}{(1 + v_{rc})} \cdot \frac{q_{vp}}{q_{ge}} \tag{1}$$

where:

q_{vp} = evaporator capacity in relation to the vapor mass flow in the refrigeration cycle (specific evaporator capacity)

q_{ge} = heat capacity input of the generator in relation to the vapo mass flow output of the generator (specific generator capacity)

v_{rc} = reflux ratio of the rectifier.

In a total backmixing of the fluid phase, the concentration and the temperature of the solution in the solution zone are uniform. The solution concentration at the head of the generator matches the solution concentration at the generator bottom. The weak ammonia solution leaves the generator in a state of boiling. The ammonia concentration of the vapor is also uniform in the generator. Since the vapor in this case is in mass equilibrium with the weak ammonia solution, the ammonia concentration of the departing vapor is minimal.

For a valuation of the axial backmixing of the fluid phase, a backmixing factor B can be defined:

$$B = \frac{c_{SL} - c_{LL}}{c_{SL} - c_{WL}} \qquad (2)$$

where:

c_{SL} = concentration of the strong ammonia incoming solution at the generator head

c_{LL} = concentration of the solution at fluid level in the generator

c_{WL} = concentration of solution in the generator bottom.

The backmixing factor B is equal to the relation of the diffusion mass flow at the fluid level and the maximum possible diffusion mass flow. Thus it describes the degree of mixing in the generator and can adopt values from 0 to 1 (0 = no backmixing, 1 = total backmixing in the generator).

Thus, with the computing program described above, the influence of the backmixing in the solution zone can be shown in figure 4, where the reflux ratio at the rectifier varies between the maximum and minimum value. When the heat pump operates at an ambient temperature of -10 ° C, a raise of 40 % of the cycle COP can be reached by completely avoiding backmixing (B =0) and using a minimal reflux ratio.

A backmixing factor of 20 % in the generator could be achieved with the developed and tested prototype (# 2) of the monovalent absorption heat pump. This resulted in a fuel related steady COP of 1.6 at the design point of 7 °C ambient temperature. In the so- called internal boiling mode, an average COP of about 1.03 is reached at ambient temperatures under - 3 ° C (fig. 5). In comparison to the absorption heat pump that has already been put on the market, (which needs an additional heating boiler), this means a raising of the mean annual COP from 1.18 to 1.40 during a complete heating period.

CONTROLLABLE CYCLE MODELING

Latest energy costs and the mean annual COP's of the low temperature heating boilers call for the development of absorption heat pumps for residential heating systems, which should amortize the costs exceding the costs of a heating boiler within five years. In order to achieve this, the absorption heat pump bearing an estimated selling price of around US $ 7,000 (in Germany DM 12,000), has to reach a mean annual COP of 1.55. The monovalent absorption heat pump described above can only reach this under the following development goals:

— The concentration of the strong ammonia solution has to be controlled in a way that the air impinged evaporator receives ambient heat even at air temperatures in a wide range below - 3ºC.
— The concentration of the weak and strong solution has to be controlled in a way that the absorption heat pump can operate at its optimal COP in all operating situations.

— The absorption heat pump has to deliver the capacity that is suited to the actual heating requirements. Thereby it is not necessary to have the conventional load water buffer, the additional load pump and the mixing valve in the heating system. An infinitely variable burner allows the heat pump to run continuously without fixed-cycle operation for more than 80% of the heating period according to the heat requirements.

. Based on extensive experimental investigation with the prototype of a monovalent absorption heat pump, it was possible to deduce process describing equations for the operating performance. These equations are the basis for a simulation program of a controllable cycle. The obtainable COP's are based on a study of parameters (without any constructive limiting conditions) with the variation of the weak ammonia and the strong ammonia solutions (fig. 6). Here, with regard to the ambient air temperature t_A, the concentration of the strong ammonia solution is adapted in such a way that there is a complete vaporization at the outlet of the refrigerant heat exchanger. If the concentration of the weak ammonia solution is varied, the result is a set of curves of constant ambient air temperature and concentration of the strong ammonia solution . Their points of inflection show the ideal curve of the COP.

For constructively given limiting conditions the simulation shows a possible function of the COP and the ambient air (fig. 5). At an ambient air temperature of - 10 °C it drops to a value of 1.48. Because of the constructive limiting condition of a solution pump with a maximum volume flow of 3 l/min, the vaporization in the air impinged evaporator breaks down at an ambient temperature of - 12 °C. The COP then again reaches values similar to those of the prototype of the monovalent absorption heat pump. Since with the changes in the ammonia concentration in this process there is also a shifting in the ammonia volume and in the solution volume in the cycle, the concentrations are defined as limiting conditions. The limitation of the storage volume to about 10 l in the condensator and about 6 l in the generator requires a limitation of the strong ammonia solution to 45 % and a limitation of the weak ammonia solution to 25 %.

Through the mode of procedure demonstrated here, the mass flow of the strong ammonia solution and of the vapor can be changed in a wide range by means of controllable valves (fig 7). In this way the specific solution mass flow reaches values between 3 and 8. This requires a special construction of the generator because its efficiency, as described above, is dependant on the backmixing in the solution zone. First experimental investigations of the energy and mass transfer in a generator laboratory test without Raschig rings show that a decrease of the specific solution mass flow results in an increase of the backmixing. In this specific generator model case without Raschig rings, backmixing factor B values up to 90 % were obtained. This negative influence on the backmixing is cancelled by installing Raschig rings and by accommodating the cross section of flow in the annular gap to this operating mode of a controllable absorption heat pump.

CONCLUSIONS

A significant limitation of a non-controlled absorption heat pump with fixed-cycle is that its process is optimized for one heating water temperatur as a function of the ambient air temperature. Therefore the air impinged evaporator works only up to an ambient air temperature of about -3 ºC, and the monovalent absorption heat pump must change into a so-called internal boiler mode. In comparison to this a controllable absorption heat pump can operate at its optimal COP in all operating situations and delivers the capacity that is suited to the actual heating requirements without a fixed-cycle operation.

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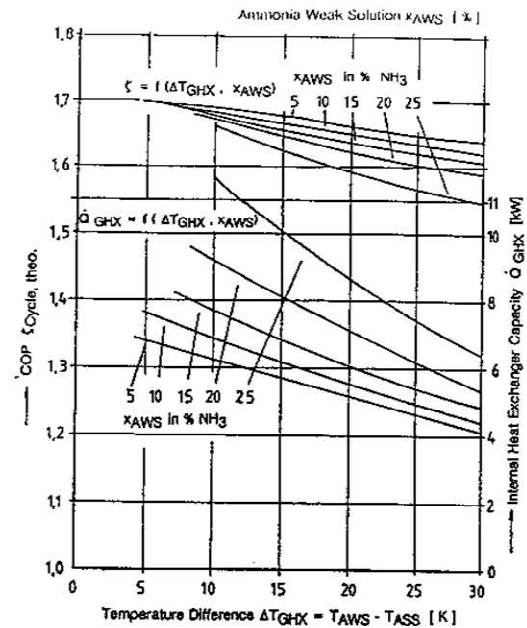
Figure 2. Parameter Computation of Heat Transfer at the Generator with Internal Heat Exchanger [1].
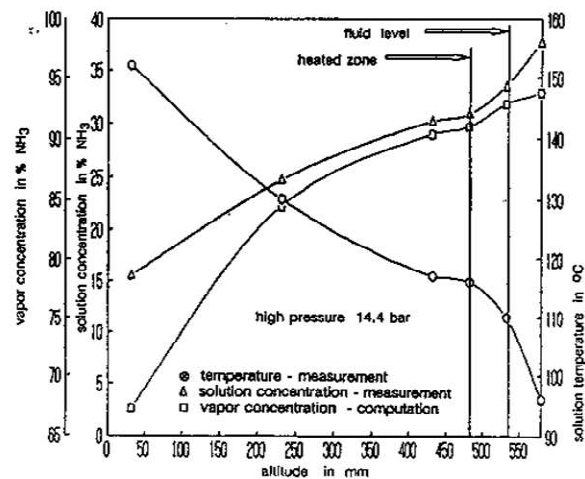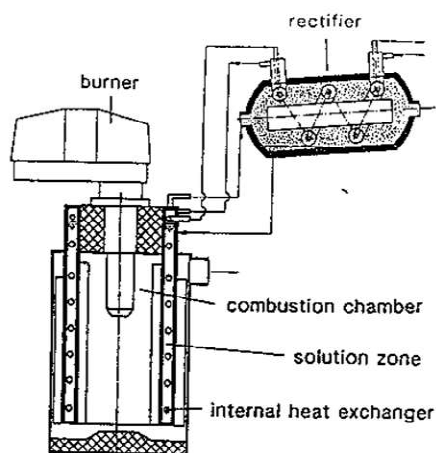Generator Input Capacity 25 KW,
Strong Solution 38 %.

Figure 1. Operational Diagram of the AHP Prototype #2
Heat-Pump-Mode. Burner Operating in Low Stage.

Figure 3a. Experimental Investigation of the Temperature-
and Concentration Profile at the Generator [1].

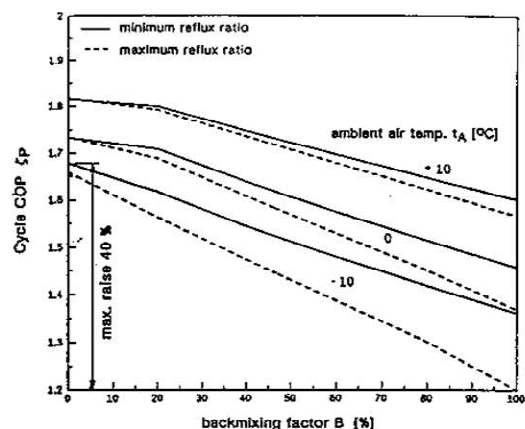| ambient air temperature	vapor concentration	spec. cycle mass flow
+ 10 °C	99.4 [%]	4
0 °C	99.8 [%]	4
- 10 °C	99.0 [%]	5

Figure 3b. Schematic Diagram of the Annular Gap Generator.

Figure 4. Influence of the Backmixing on the COP [7].
COP $\zeta_P = (Q_{abs} + Q_{cond}) / Q_{gen, input}$
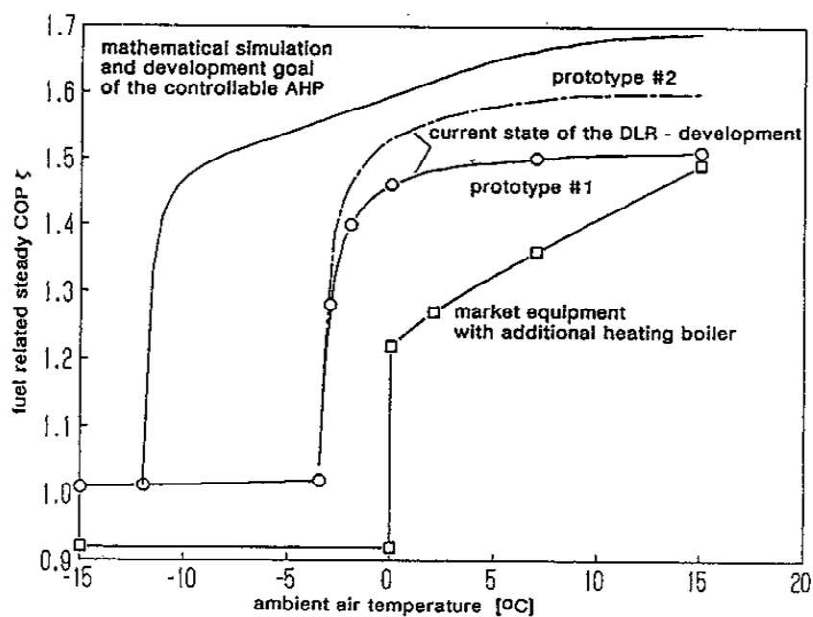

Figure 5. Progress in Absorption Heat Pump Development for Residential Heating Systems.
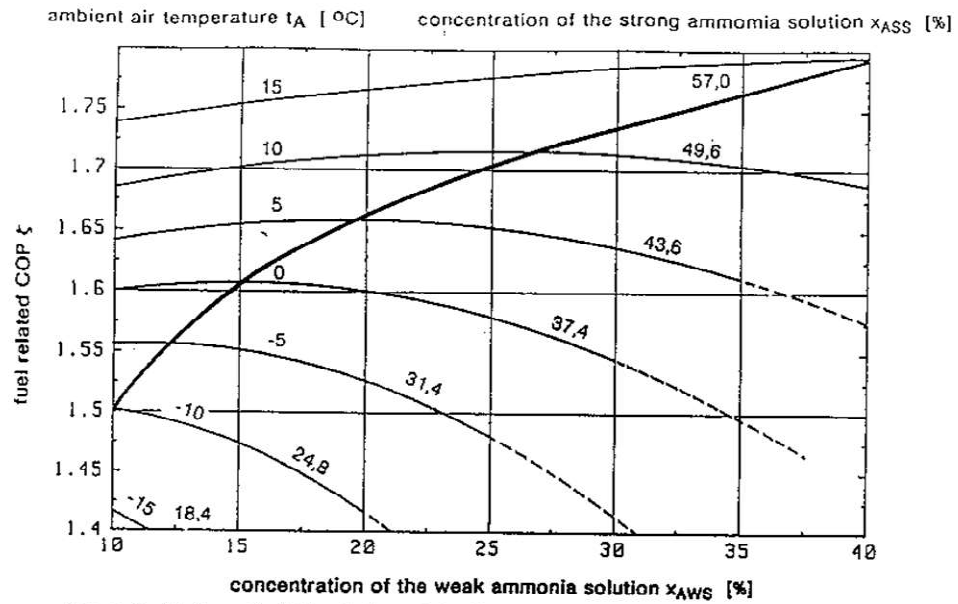Burner capacity is determined by lower heating value of fuel oil.

Figure 6. Mathematical Simulation of the Concentration Controllable AHP Process for a Heating System. COP Including the flue gas condensing heat exchanger. Hot water temperature 50 / 40 °C at the ambient air temperature of -15°C. Burner capacity is determined by lower heating value of fuel oil.
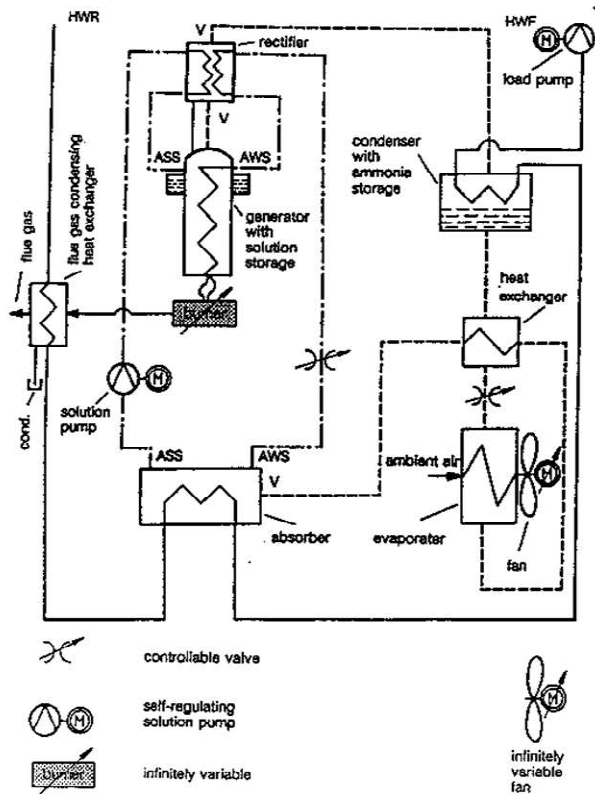

Figure 7. Operational Diagram of the Controllable Cycle.

controllable valve

self-regulating solution pump

infinitely variable

infinitely variable fan