Evaluation of a hygroscopic condenser

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Abstract

In Sweden the industries releases about 50 TWh/year of low temperature waste heat\(^1\), often in the form of humid air flows. Today, conventional flue gas condensation is only exploiting a minor part of the energy from these flows. It is a well-established and profitable way of improving the efficiency of district heating plants and other boilers for wet fuels. However, the condensation is only applicable when the dew point of the flue gas is above the temperature demand for the heating net. The paper industry gives a good illustration of the limitations for conventional condensation: several MW of wet air streams with dew points of 60-65\(^\circ\)C are released but cannot be recovered since the temperature demand is 70-80\(^\circ\)C for the heating net. Different technologies for more advanced waste heat recovery are developing and this report is evaluating a demonstration plant for “hygroscopic condenser”, which uses a hygroscopic solution that allows condensation above the dew point. The hygroscopic solution is potassium formate, which enables condensation to start about 20\(^\circ\)C above the dew point and is sufficiently non-toxic and non-corrosive.

The objective of this work is to evaluate both the equipment and the process during some initial tests at the paper mill at Holmen, Braviken. The aim is also to suggest improvements of the process, the components and the additional equipment for future continuous operation.

The equipment consists of two main parts: a hygroscopic absorption stage and a regeneration stage. The major part of the humid air is led into an absorption column where vapor is absorbed by the formate solution and rises its temperature. This recovered waste heat is transferred to the heating net by a plate heat exchanger. The regeneration unit is used to maintain the hygroscopic concentrations by evaporation of vapor from the formate solution (amount of absorbed vapor = amount of evaporated vapor). The regenerator is driven by process steam from the existing 3.5 bar net. The evaporated vapor is led to a conventional condenser where the regeneration energy can be recovered and the condensate is bled off. The recovered heat from the process (hygroscopic absorber + regeneration condenser) is used in the heating net at Holmen, Braviken (VVG-net).

The initial tests have been made during 15 hours of initial operation, when the equipment has delivered about 3 MWh in total. The tests show a good temperature performance since the dew point of the humid air has been lowered from about 60\(^\circ\)C to 47\(^\circ\)C. The recovered heat was used for heating from 65\(^\circ\)C to about 80\(^\circ\)C. During the initial tests the capacity has not yet reached the design values. As an example the delivered heat was measured to 280 kW where-of 46 kW from absorbed vapor, 129 kW from the sensible heat in the incoming humid air and 105 kW from the regeneration. The bottle-neck parts of the equipment have been localized and will be overseen during the summer of 2011 and the process is planned to be in use during the autumn with an output capacity of 500 kW. The coefficient of performance (COP) is calculated to just below 2 during normal operation but was about 2.7 in the test runs due to the high portion of sensible heat.

Keywords: Hygroscopic, condenser, waste heat, heating, absorption, heat pump, pilot plant

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\(^1\) Förekomst av industriellt spillvärme vid låga temperaturer, Ingrid Nyström, Per-Åke Franck, Industriell Energianalys AB, 2002-04-15
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1. Introduction
From many plants today there is low temperature waste heat, for example wet gas at mediocre temperatures, which flows out from the system. These flows do often contain a large amount of energy which is not taken care of because the temperature is below the requirement for central heating. A major part of the energy which is possible to extract, is the condensation enthalpy for the vapors in the flow. For boilers using wet biofuels usually a condensation step is added for this reason and the energy is used in district heating nets. However, some flows have a dew point which is too low for extraction of any usable energy for direct heating. For these flows a heat pump is necessary. Today there are many types of heat pumps, from absorption heat pumps to electrical ones.

This report is concentrated at a hygroscopic heat pump, and the fitting of it to a humid gas flow at the paper mill of Braviken. The hygroscopic heat pump uses process steam at 3.5 bar as driving energy. In this way energy could be upgraded in an easy and cheap way.

The objective of this work is to evaluate the performance of the equipment and the process during some initial tests at the paper mill at Holmen, Braviken. The aim is also to suggest improvements of the process, the components and the additional equipment for future continuous operation.

2. Theory

2.1 Properties for the hygroscopic solution (potassium formate)
A hygroscopic substance is a substance which has water absorbing qualities. This means that vapor is absorbed even when the vapor pressure is too low for ordinary condensation. This also means the water will not evaporate as easily as from the pure water, which can be quantified as a boiling point elevation or dew point reduction. Applications for hygroscopic solutions, among many, are as dust laying agents and drying agents. In this application example of hygroscopic salts are lithium bromide and salts of potassium and sodium, but it could also be substances like hydroxide or phosphoric acid. A property that is wanted, except for the boiling point elevation, is stability in solution with water. Other desirable properties are low/non corrosion and low viscosity, which would give a lower resistance in pipes and more turbulent flows which increase the heat transfer in heat exchangers and at last, a low price. The solubility of the salt is a vital question since high concentration of the salt is necessary to reduce the partial pressure of the water and at the same time, the increased concentration will also risk crystallizing which may result in clogging of heat exchangers. In the Braviken plant potassium formate is used due to its corrosion properties and also because it is quite cheap.

The properties of the solution are essential for the capacity of the equipment. The parameters are therefore described in the following text.

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2 Performance evaluation and simulation of a new absorbent for an absorption refrigeration system, 2003
3 Ella Nymark, Chemtronica AB, 101028
The major risk with potassium formate is crystallization. As seen in Figure 1, the solubility correlates by the temperature. The problem is that the coldest part of the equipment, the VVG-heat exchanger (district heating), also is the most sensitive for crystals. The equipment will keep a temperature at, in the coldest place, about 65°C. This means there is no problems with concentrations up to 80w%. However, the equipment will stand still from time to time. The heat will escape from the equipment and the temperature will be reduced. The following graph shows when the solution risks crystallizing.

Figure 1: Solubility of potassium formate in water at different temperatures

Figure 2: Crystallization temperature in °C

4 National Institute of Standards and Technology (NIST)
It is easy to see that the risk for a crystallized solution increases fast at concentrations above 77w%. The good side is that if the solution is diluted to 50w%, the equipment will be able to handle down to -50°C and dilution to about 70 w% would be adequate to cope with crystallization at temperatures around 0°C. These two graphs show the highest concentration which may be allowed. The problem is that a low concentration gives less hygroscopic force. Too further illustrate this effect, Figure 3 shows the boiling point elevation.

![Boiling point vs concentration](image)

**Figure 3: Boiling point versus mass fraction of potassium formate.** The elevation is dependent of the temperature and these values are only valid for the boiling point. A graph which shows the elevation of the dew point can be viewed in the appendix.

The boiling point elevation is exponential and the increase of hygroscopic effect is steeper at higher concentrations. This means every percentage point is important. In the process the boiling point will be avoided due to a practical reason which will be described later. To see how the effect is working at temperatures below the boiling point, a plot can be seen in appendix. It the graph it is seen that the hygroscopic effect is not only dependent on the concentration, but also of the temperature (larger effect at higher temperatures). The equipment is designed for work in a region between 70 w% and 80 w%. This gives an elevation of the dew point between 20°C and 45°C. The concentration will reach an equilibrium which will depend on the energy transferred in the regeneration and the humidity in the wet air stream. To understand how much more energy that may be extracted with a higher concentration, figure 4 shows how a gas with a dry temperature at 160°C and a dew point at 60°C at the inlet may be used. It is important to know that the energy from the sensible heat makes a large part of the total extracted energy, though a larger part might be taken from the condensation energy.

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5 Formate Technical Manual, Part A: Chemical and Physical Properties, Section A5: Crystallization Temperature
6 Section A3; Water activity and colligative properties, Cabot specialty fluids
The equipment will use water at a temperature of 65°C for the cooling of the hygroscopic solution. This means the temperature of the wet air may only be lowered to 65°C at the most. If only the sensible heat is to be recovered, only 100 kW may be extracted. At 78w% this value increases to about 350kW. However, the sensible heat, which still is seen as waste heat, can be recovered without any regeneration of hygroscopic solution. Therefore the COP will be infinite when no water is absorbed. When water starts to be absorbed, energy is needed for evaporation to be able to store the concentration of the hygroscopic solution. The evaporated water is collected in an ordinary condenser and therefore, the interesting form of the next two graphs looks like it does. All vapors which will be absorbed must be evaporated. The evaporation energy does not differ so much between the temperatures in the system and by that, the COP goes towards 2.
### 1.1.1. Density

To know the concentration of potassium formate in the solution the density must be measured. The density depend on three variables, first is obviously the concentration of formate, which will increase the density with a higher concentration. This is the most important variable due to the major increase of density with a higher concentration. The second variable is the temperature. A higher temperature will result in a lower density though the difference it quite

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7 Calculated from Mats Westermark excel sheet
8 Calculated from Mats Westermark excel sheet
small. It is still important take the temperature into account when calculating the density due to the need for exact numbers for calculation of the performance. At last the pressure will have an effect on the density though this will not affect much at all. For all the measurements, the pressure has been constant. This means the equation for deciding the concentration, the pressure is included in the constants.

1.1.2. Biodegradability
For a fluid which might escape it is very important it is degradable in nature. Potassium formate is toxic and works as a biocide at high concentrations but when diluted it can be degradable in a short time\(^9\). This means there is no risk of bacterial growth in the system and if there is some formate escaping, the problem is not severe. The only risk with releasing potassium formate is the risk of eutrophication in nearby lakes. The amounts that might escape under normal operation in this case are extremely small and due to that, cleaning equipment is used.

1.1.3. Compatibility with elastomers
Potassium formate is compatible with the most elastomers except for those which are sensitive for alkaline surroundings. In tests done by Cabot specialty fluids, two types of rubber have compatibility problems with potassium formate. These are NBR and FKM (Viton)\(^10\). The problems will be affected by the temperature of the surroundings, with less compatibility at higher temperatures. Due to the high temperature and the high concentrations in this process, no parts will be made by these two types of rubber.

1.1.4. Compatibility with metals
Potassium formate is a salt which has very small effects on metals. This is thanks to properties like it is a good antioxidant, it keeps and favorable alkaline pH and the lack of halides. Nevertheless, there are no tests of the effect potassium formate has on different metals in the type of surroundings which occur in this process. There are tests of the effects on metals though, in the oil drilling industry where different types of brines are used. The surroundings are not entirely the same with a higher pressure, but the temperature used is in the same range. In their tests there are very small effects of corrosion done by the potassium formate. To be on the safe side, the process is made from stainless, acid-resisting steel, but tests are made with ordinary stainless steel as evaluation as future building material.

1.2. Flue gas
This type of plant can extract energy from many types of flows. In this report a humid gas from a paper mill is used. The air is collected from beneath the wire in the paper machine. The air might contain fibers which escaped from the process. These could be a problem, if it appears large quantities, in the heat pump due to clogging. If there is a problem with this, a solution could be to remove the fibers before the inlet, with a scrubber, particle filter or just clean the bottom of the regeneration equipment, where the eventual fibers probably would

\(^10\) Formate Technical Manual, Part B: Compatibilities and interactions, Section B7: Compatibility with elastomers
gathering. There is also a risk of pollutions from the flow due to the use of recycled fibers in the plant (in the recycled fibers there are ink and additives) but also due to lignin mm, which also are soluble in water\textsuperscript{11}, from the wood. This might affect the properties of the hygroscopic solution if it is not cleaned or changed regularly. The amounts are very small though and therefore no cleaning equipment will be added into this study.

3. The hygroscopic process

The process can be divided into three steps: hygroscopic absorption, flue gas condensing and regeneration. Depending of the property of the flue gas the arrangement between the steps can change. If the flue gas is hotter, then the regeneration step can be put in the front of the process. For this application, the wet air does not contain enough latent energy to be able to regenerate itself. The process scheme is showed in the appendix.

1.3. Hygroscopic absorption

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure7.png}
\caption{Flow sheet for the absorption part (black line is the flue wet air flow, yellow line is the hygroscopic flow, blue line is the district heating flow)}
\end{figure}

\textsuperscript{11} Marie Lindeberg, Holmen paper, Braviken
In the hygroscopic absorption step, the vapor is absorbed by potassium formate. The salt increases the boiling point which makes more vapors condense which in turn transfers more energy to the salt solution. The salt and water solution is pumped from the bottom of the column to a heat exchanger where the energy, in this case, is used for heating of process water. From the heat exchanger the solution is sprayed into the top of the column again. Due to the vapor condensing, the potassium formate will be diluted with water which results in a lower boiling point elevation. This means the solution needs to be regenerated for the equipment to be able to work in the long term. Therefore the salt/water solution is pumped to a regeneration step. The incoming humid air has a dry temperature between 140 and 160°C and might be able to damage the plastics in the column. Therefore a part of the flow to the regeneration is forwarded to the air inlet where it is possible, if necessary, to cool the air before it comes into contact with any plastics.

1.4. Regeneration

The mixture of potassium formate and water is sprayed into a regeneration heat exchanger. To be able to concentrate the solution, process steam from Braviken is added (3.5 bar and 139°C). The flow of wet air through the regeneration is mainly to lower the vapor pressure. This makes it possible to evaporate more water from the solution at a lower temperature.
There is also a positive side effect in the form of transferred heat from the hot wet air. In some cases where the wet air is hotter, it could provide all the energy necessarily for the regeneration without any additional heat from steam. The mixture is pumped in a circuit until the concentration is satisfying and thereafter pumped back to the absorption step. A problem with the regeneration is the boiling point elevation. The 3, 5 bar steam used condenses at roughly 139°C. This means that the solution can only be concentrated by boiling to a certain level. In this case, the theoretical level is between more than 71% and 73%. To boil the solution is also not satisfactory due to the boiling creates a film of vapor between the fluid formate and the heat exchanger wall. This gas layer would make the formate film drop of from the surface and increase the resistance against heat transfer. The alternative is to evaporate the solution at a dew temperature at about 80-90°C. This means a better heat transfer but also the possibility to increase the concentration to above 75%, though it would take longer time due to the lower driving force. When the steam has condensed, it still has the same temperature as the steam. To be able to recover this heat the flow is forwarded to the condenser where it will be cooled down to about 60°C.

1.5. Flue gas condensation

The flue gas from the regeneration is forwarded to a condenser that recovers the energy used for evaporation. The energy is transferred to the district heating net. The high pressure (3.5 bar) condensate from the regeneration is forwarded to the upper part of the condenser to be able to recover the last energy from 139°C to about 60°C. The cooled condensate together
with the condensate from the wet air stream is forwarded to the sewage system. The air leaving the condenser is assumed to be saturated.

1.6. Piping

Equipments handling potassium formate, are often made from stainless steel of grade 304. With this type of steel the risk of corrosion is limited even though the formate is in a high concentration. The type of equipment is often cooling equipment, and the temperature will not be a problem. In this equipment though, the temperature will be quite high (above 100°C) and this increases the risk of corrosion. Therefore the piping is mainly made from the stainless, acid-resisting steel of grade 316L. This steel contains molybdenum which increases the chemical strength, but also increases the price.

1.7. Equipment for measurements

In the system, there are four different types of values which are measured, temperature, pressure, density and humidity. However, only some of the temperature sensors are attached to the operating system. The connected temperature sensors are of type Pt 100 which together with a transmitter delivers 4-20 mA. The rest of the temperature sensors are thermocouples of type K. These are manually controlled and are not important as guidance for the system. The humidity, density and pressure indicators are, unlike the temperature indicators, self designed and therefore a more detailed explanation follows.

1.7.1. Humidity

Humidity is measured by the use of a wet thermometer. This will show the wet bulb temperature and from this, it is possible to calculate the humidity with the help of two assumptions. First that all heat transfer is done by convection. The second assumption is that the velocity of the air around the wet bulb gives no difference in mean molecular weight.

The heat transfer can be described as:

\[ Q = hA(T - T_{wet}) \]

Where

- \( h \) = heat transfer coefficient
- \( A \) = transfer area
- \( T \) = air temperature
- \( T_{wet} \) = the wet bulb temperature
- \( Q \) = Heat transfer

The second transfer is the mass transfer from the thermometer to the air. This can be described as:

\[ W = h_d A \frac{M_w}{RT} (P_{w0} - P_w) \]

Where

- \( h_d \) = mass transfer coefficient
- \( A \) = transfer area
M_w = Molecular weight of water
R = Universal gas constant
T = temperature in Kelvin
Pw0 = the saturated partial pressure of vapor
Pw = the actual partial pressure of vapor
W = Mass transfer

The mass transfer will consume the heat transfer by the equation:

\[ Q = W \ast \lambda \]

\( \lambda \) = vaporization energy

This gives:

\[ hA(T - T_{wet}) = h_dA \frac{M_w}{RT} (P_{w0} - P_w) \lambda \]

which can be rearranged to equation (1):

\[ P_w = P_{w0} - \frac{h(T - T_{wet})RT}{h_dM_w \lambda} \]

The unknown value of \( h/h_d \) can be estimated by the two following equations (2):

\[ \frac{h}{h_d \rho_a} \approx 1 \]

Where:
\( \rho_a \) = density of surrounding gas

This equation is only valid for water/air systems, and equation (3)

\[ \rho_a = \frac{m_a}{V} \]

Which together with the ideal gas law gives (4):

\[ pV = nRT = \frac{m}{M}RT \gg \frac{m}{V} = \frac{pM}{RT} \]

(1), (2), (3) and (4) together gives the following equation:

\[ P_w = P_{w0} - \frac{pM_a(T - T_{wet})}{M_w \lambda} \]

### 1.7.2. Density

The density sensor is made by a weight which almost floats in the potassium formate. The floating force of the weight is measured by a scale and this together with the temperature at
the solution and the mass of the weight makes it possible to through some approximations get the density. The first approximation is that the fluid is incompressible and will not be affected at different pressure. The following graphs show the dependent of temperature and pressure at one concentration.

![Graph of SG=1.58 at 25 °C](image1)

**Figure 10:** Temperature and pressure dependency of density at the same specific gravity. The pressure is in MPa

![Graph of SG=1.88 at 25 °C](image2)

**Figure 11:** Temperature and pressure dependency of density at the same specific gravity. The pressure is in MPa
It is easily seen that the pressure dependency is very small compared to the temperature dependency and that an approximation to exclude it from calculations is ok. From the values in the graphs above, and approximated equation has been extracted which will gives the specific gravity depending on the temperature.

\[ s_g = s_{g25\degree C} - 0,0008(T - 25) \]

Where
\( s_{g25\degree C} = \) specific gravity at 25 \( \degree \)C
\( s_g = \) specific gravity at T \( \degree \)C (same solution as \( s_{g25\degree C} \))
\( T = \) Temperature in Celsius

This equation together with the equation

\[ C = (30,222916 * s_g^3) - (183,0869 * s_g^2) + (449,9977 * s_g) - 297,1264 \]

Where:
\( C = \) concentration in w\%

The equations together give:

\[ C = (30,222916 * (s_{g25\degree C} - (0,0008(T - 25)))^3) \]
\[- (183,0869 * (s_{g25\degree C} - (0,0008(T - 25)))^2) + (449,9977 * (s_{g25\degree C} \]
\[- (0,0008(T - 25))) - 297,1264 \]

A picture and a schematic drawing of the sensor can be viewed in the appendix.

1.7.3. Pressure sensors for packing

The pressure is measured by a u-pipe where the difference in water level shows the pressure in mmVp (millimeters of water).

1 mmVp = 9,81 Pa

A picture and a schematic drawing of the sensor can be viewed in the appendix. The main reason for this measurement is to be able to see if there is any clogging in the hygroscopic column.
1.8. Automatication system
The system is supposed to be able to take care of itself in the future, but at this pilot plant there is a mix of atomized and manual adjustments. The regulating parts and the parameters which affects are listed below.

3.6.1. Bypass fan, FL-001
The rate of speed for the fan will be controlled, through a thyristor, manually.

3.6.2. Regeneration fan, FL-002
The rate of speed is guided by the temperature difference between the inlet into the system (TIC 01) and the temperature between the fans (TIC 05). The temperature different should equal approximately 20°C. When the difference exceeds this temperature, the fan will reduce its speed which in turn will lower the temperature difference by reducing the cooler flow from the regeneration.

3.6.3. Pump for regeneration, P-001
The rate of speed for the pump will be controlled manually between two states, on and off. When the formate surface falls below a certain level in the tank, the pump will automatically turn off by a low level guard (LS 01).

3.6.4. Pump for district heating, P-002
The pump is guided variable by the temperature out into the district heating net. The equipment will be parallel with the ordinary district heating source and therefore it is important to deliver the same temperature on the water. In this case this temperature is 80°C. If the temperature is below this value, then the pump will decrease the number of revolutions, which in turn will increase the time for the water in the heat exchanger which will increase the temperature. The pump will have a minimum flow programmed which it cannot fall below. This is due to the time the water needs to travel the distance from the heat exchanger to the measurements. If the pump would stop, the heated water would never reach the indicator which in turn never would start the pump again.

3.6.5. Hygroscopic absorptions pumps, P-003 and P-004
The pumps at the hygroscopic tower will be guided by the temperature at the bottom of the tower (TI 18). The temperature must be above the temperature out in the district heating net, and still contain the necessary heat to be able to overcome the driving force needed in the heat exchanger. The temperature for this is 85°C. If the temperature increases the pump will increase the flow which would increase the heat transfer through the heat exchanger and result in a lower temperature again. For protection of the pump, a low level guard (LS 02) will prevent it from pumping air.

3.6.6. Steam trap
A steam trap is placed after the steam side of the regeneration. It sees to that only water will be able to leave from the regeneration. This means it will control the steam flow through the system. If more energy is transferred more steam will condense, which in turn will flow through the steam trap, which means a larger flow.
3.6.7. Float valve
The flow to the regeneration will be controlled by a float valve. If the formate level in the tank increases, the flow will be decreased by the valve. This in turn will result in a lower surface level. The float valve’s major task is to contain the level in the regeneration. By doing so, it will also regulate the level in the hygroscopic absorption. This is due to there is a fixed amount of formate solution in the system.

1.9. Characteristics
This system is able to take care of itself thanks to the float valve which will secure a proper volume of hygroscopic solution in both tanks. Values in the equipment will be possible to keep watch on and it will be possible to change the velocity of all engines. The flow between the systems will still be controlled by the float valve and not possible to change by remote. This must be done by the manual valves between. The same is for the amount of steam used. The steam trap results in that only condensate will be released. This means the amount of steam will be controlled by the amount of energy the medium on the other side of the heat exchanger will be able to recover.

2. Effects which could affect the process
There are many effects and additives which could be used to increase the efficiency of the process.

2.1. The Marangoni effect
In a fluid the concentration and temperature will differ through the volume. This is due to the complexity of the combination of heat transfer combined with different kinds of mass transfer as diffusion. The temperature and concentration will change the surface tension which in turn will change the surface area.

The larger surface area will increase the mass and heat transfer area which in turn will make the equipment for the same transfer smaller. The effect can for example be viewed in a glass of wine where the concentration gradient between ethanol and water gives the gradient in surface tension (Tears of wine). This effect becomes even greater with dessert wine where also the sugar concentration results in another gradient. Below, a sweet dessert wine is revealing the effect by its shadow.
To increase the effect surface active additives can be added. These additives can make the surface more instable or and therefore also larger but it can also make the surface more stable. Octyl alcohol and 2-ethyl-1-hexanol is sometimes used as additive in absorption refrigeration machines to get a better efficiency\textsuperscript{15}. The difference in this case from the refrigeration machines is that the equipment is an open cycle. This means there is a risk that the additives will evaporate and follow the air to the outlet and be lost. A solution to this problem could be a condenser in the air outlet, but due to the uncertainties there will not be any additives in this pilot plant, but it is a recommendation to look more deeply into the area for future usage.

2.2. \textbf{Ultrasonic vibrations}

Ultrasonic vibrations can be used in the process to increase the surface area where the mass and heat transfer occurs. However, it is expensive to create the vibrations artificially for this purpose only and the profit would probably equal the losses.\textsuperscript{16} But, in the paper industry there is an asset in form of vibrations from the process. Though it is not shown these vibrations are in the desired frequency or in sufficient amount.

\textsuperscript{14} Picture is capture from “en.wikipedia.org/wiki/file:wine_legs_shadow.jpg” 2011-02-07
\textsuperscript{15} Effect of heat transfer additives on the instabilities of an absorbing falling film, Wei Ji and Fredrik Setterwall, department of chemical engineering and technology, KTH, 1995
\textsuperscript{16} Ultrasonic vibrations for improving absorption chillers performance, F. Rossi, M. Filipponi, A. Presciutti, Industrial engineering department, University of Perugia
2.3. Crystallization inhibitors
Due to the high concentration of potassium formate there will be risk of crystallization. When the temperature drops, the risk increases for clogging in the system. There are two scenarios where this additive could be useful. First, it could be possible to increase the concentration of formate which would make it possible to extract more water from the wet air stream. This would give more extracted energy but also a need for more energy in. It would also become a problem due to the lower temperature gradient that could be used for heat transfer in the regeneration. This means a larger transfer area or/and slower streams would be required. Second, the lower crystallization temperature could be used for storage of the equipment when not in use. This means it should be able to handle outside temperatures which, in Sweden at wintertime, sometimes reach down towards -40°C. In tests for lithium bromide cooling machines, inhibitors have lowered the crystallization temperature with up to 13 K. This together with other solutions could help to store the equipment without first emptying it of potassium formate. Crystallization inhibitors often have some more properties except for the anti-freeze one. One example which could be useful is anti-corrosion, but there is more.

3. Safety against crystallization
Crystallization in the equipment might happen at two different kinds of moments. First is the risk for crystallization when the equipment is in operation. This happens when the temperature approaches the solubility temperature for a certain concentration. This could be avoided by always keeping a safety margin to the crystallization temperature. The second moment is when the equipment is not running and it adapts to the temperature of the surroundings. If the temperature is really low, the solution will freeze and result in both clogging, which could be difficult to get rid of, and also frost erosion which might destroy pumps, pipes and more. To keep away from this, there are some different solutions.

3.1. Dilution of the potassium formate solution
When lowering the concentration of formate the crystallization temperature also is reduced towards the minimum at 50w% which can handle down to -50°C. Potassium formate is actually used as a de-icing agent thanks to it good properties at medium concentrations. The downsides of this proposal are that it will cost energy to increase the concentration back to the working values and that this will only work when there is time to prepare for a stop in the operation. This means it is a good way for planed longtime storage when the solution not has to be concentrated now and then, but there has to be some emergency system for unplanned stops.

3.2. Operation with steam only
If there is a stop in the paper machine and there is still steam available, the process could continue without any wet air. This could be done by adding water to the system and collect it at the condenser. In this way, the temperature could be preserved and a large part of the

17 Testing of crystallization inhibitors in industrial LiBr solutions, James A. Dirksen, Terry A. Ring, Kristin N. Duvall, Nathalie Jongen, Department of chemical engineering, University of Utah, 2001
energy from the steam would be recycled to the district heating. There would be an exergy loss though.

3.3. Crystallization inhibitors
Inhibitors can be added as mentioned before. These could help decrease the freezing temperature but to rely on only this could be difficult. It could be a good complement to the other solutions by giving a lower temperature which needs to be reached for crystallization. This means there is more time to dilute the system with water before it start to crystallize.

4. Economy
The price per kWh district heating today is around 0, 38 SEK\textsuperscript{18}. It is produced in three different types of boilers, a wood residue boiler, an electric boiler and an oil boiler. The price is varying during the year due to the oil and electric price but this is measured at a time when the electric and oil price is above normal. This due to an oil crisis with Libya in the middle and that it is a cold season with a large electric consumption. However, the value can be used for comparison as long as the knowledge, that this is a quite high price, exists.

The idea of the equipment is that it shall make the user’s energy usage more effective and by that, reduce their total costs. This is still a pilot plant which is built for tests and ideas for future commercial units. This means the equipment will not be optimized and therefore may the economy calculations not be fair to the equipment. However, it could be interesting to see how this equipment can handle around different solutions as for example, the possibility of buying the energy from the local district heating net. The cost for the hygroscopic is showed in the table beneath. Today, the equipment uses between 12 and 22 kW of electricity. The cost for this is not taken into account in the calculations below. Neither are maintenance costs. Instead the depreciations are set to occur during a shorter time.

Table 1: Price per delivered kWh of hot water to the district heating net

<table>
<thead>
<tr>
<th>Investment</th>
<th>1200000 SEK</th>
<th>1200000 SEK</th>
<th>1200000 SEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pressure steam (inclusive tax)</td>
<td>0 SEK/kWh</td>
<td>0,2 SEK/kWh</td>
<td>0,4 SEK/kWh</td>
</tr>
<tr>
<td>Depreciation [years]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>COP</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cost [SEK/kWh]</td>
<td>0,02</td>
<td>0,12</td>
<td>0,22</td>
</tr>
</tbody>
</table>

\textsuperscript{18} Measured 4/4 2011 during a 24h period. Measurement is done by the heat distribution central at Braviken.
4.1. Costs of district heating

Table 2: Prices of district heating for 2011 and for private persons. The pay-off time is calculated with a cost of 0,4 SEK/kWh of steam.

<table>
<thead>
<tr>
<th></th>
<th>Fortum</th>
<th>Vattenfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stockholm(^{19})</td>
<td>Hofors(^{20})</td>
</tr>
<tr>
<td>SEK/year</td>
<td>5625</td>
<td>5625</td>
</tr>
<tr>
<td>SEK/kWh</td>
<td>0,655</td>
<td>0,606</td>
</tr>
<tr>
<td>Pay off time, year</td>
<td>0,69</td>
<td>0,75</td>
</tr>
</tbody>
</table>

The pay-off times mentioned in the table above, are the time during the income from the hygroscopic condenser would equal the investment. It is calculated with the price for each district heating cost. The cost for used steam to the process is set to 0,4 SEK/kWh. All costs for the hygroscopic process are estimated and therefore the pay-off time above should only be used as a guideline. The prices are also for buying district heating and not producing which gives a more expensive cost due to the profit for the producer. It is also with included taxes.

4.2. Electric heat pump

Another way of extracting energy from the wet air stream is by using an electric heat pump. This means a better COP, and more energy transferred, but it also means an exergy loss due to the electricity the compressor needs. The cost for an electric heat pump is about 1500-2000 SEK/kW\(^{23}\) which means between 1, 5 and 2 million SEK for an equipment which can deliver 1 MW. This can be compared to the hygroscopic equipment which costs between 1 and 1, 5 million SEK. The COP for this type of heat pump, and the wet air flow as heat source would be approximately 4\(^{24}\). The COP for the hygroscopic heat pump is almost 2. The choice between these two depends on the different types of energy flow which can be used. If there is cheap low pressure steam nearby, the hygroscopic heat pump costs will almost equal the maintenance/depreciation costs.

\(^{19}\)http://www.fortum.se/document.asp?path=19923;22344;22353;23972;39285;39286;39308;39310;53474;53513;53514&level=4

\(^{20}\)http://www.fortum.se/document.asp?path=19923;22344;22353;23972;39285;39452;39453;53634;53635;53639&level=4


\(^{22}\)http://www.vattenfall.se/sv/file/Prislsta__verkalix_2011_15926123.pdf

\(^{23}\)Gustav Jansson, AKJ ENERGITEKNIK AB, 2011-02-28

\(^{24}\)Gustav Jansson, AKJ ENERGITEKNIK AB, 2011-02-28
Table 3. Price per delivered kWh of hot water to the district heating net from electric heat pump

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>2000000 SEK</td>
</tr>
<tr>
<td>Electric price (inclusive tax)</td>
<td>1 SEK/kWh</td>
</tr>
<tr>
<td>Depreciation</td>
<td>10 years</td>
</tr>
<tr>
<td>COP</td>
<td>4</td>
</tr>
<tr>
<td>Price per kWh district heating</td>
<td>0,3190 SEK/kWh</td>
</tr>
</tbody>
</table>

At Holmen, there are three types of production units for low pressure steam. A wood fired boiler, an oil boiler and an electric boiler. The one which delivers the most expensive steam is the oil boiler and there for the margin price depends on the oil price. But the hygroscopic heat pump returns the heat at a lower exergy and therefore, the price should be the mean price.

5. Measurements
The main objective for the measurements will be to investigate how the different parts shall be designed/scaled for future equipments and to investigate with which values at given parameters the equipment will work the best way. This is not necessarily the same as it will have the best efficiency. This is due to the fact noticed earlier in the report, that the COP drop’s when the heat output increases.

It is also important to investigate how well it works in this application and how it stands in the competition of other kinds of equipments. The COP and also the heat output versus cost will indicate this.

The COP is normally defined as follows:

$$COP = \frac{Heat \ output}{Heat \ input}$$

For this equipment the COP will be defined as.

$$COP = \frac{Heat \ from \ hygroscopic \ absorber + Heat \ from \ condenser}{Heat \ to \ regeneration \ from \ low \ pressure \ steam}$$

This is due to that the energy in the wet air is assumed to be waste heat which would be thrown away without this equipment.

It is also interesting to see how much the dew point will be lowered. This is done by measuring the wet bulb temperature together with the temperature in both the inlet and the outlet.

5.1. Regeneration
The most important measurement in the regeneration is the amount of water which can be evaporated. All condensed water in the equipment will have to pass through the evaporation stage and therefore, this amount is a measurement of the total effect. The actual amount will

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25 Thomas Holmén, responsible for the department of technology at Braviken, 2011-04-05
be compared with the designed amount to get a view of how the equipment shall be constructed in the future. This is done by measurements during steady-state operation with the whole equipment. The driving force in is calculated from measured values and later compared with the designed values. The driving force in the regeneration is the difference in temperature which is needed for the evaporation. It may be described as

$$T_{force} = T_{steam} - T_{dew \ point} - T_{hygroscopic \ force}$$

One more interesting part which will be measured is how the concentration of potassium formate will affect the driving force and by that, the evaporation. The high concentration of potassium formate will give a higher boiling point which in turn will reduce the mass transfer velocity from the fluid to the gas phase. Because the evaporation energy is the same, the same amount of energy is needed, and not more. This gives the velocity reduction can be avoided by a larger driving force which in this case is the temperature or with a larger transfer area. The effect which is transferred between the phases is measured by the amount of condensate per time which is created from the steam.

5.2. Condenser
The condenser will be evaluated by measurement of the condensate and the temperature difference between the sides in the heat exchanger.

5.3. Hygroscopic condenser
The hygroscopic condenser will be evaluated by measurements of the condensation versus the concentration of hygroscopic solution.

5.4. Fans and pumps
All engines will be tested to see if they are capable of delivering the flows which they are designed for. This is done by measurements of the number of revolutions during steady-state compared to the maximum value and the flow in the equipment.

5.5. Type of steel
Due to the face that the stainless steel of grade 304 is cheaper than the stainless steel of grade 316\(^{26}\), a major saving can be done in future equipment if the cheaper one is used. To know if it can handle the combination of a high formate concentration and high temperature, the demister above the regeneration is made by steel of grade 304. The reason for this placement is the combination of the highest temperature together with the air which contains oxygen, water and some formate is achieved here. If the sample is not affected by the surroundings, the grade 304 steel can be considered to use in future equipments. The sample will be controlled by ocular means.

5.6. Test planning for equipment

5.6.1. Tests of functionality

First test
Before any tests with potassium formate is done, a run with only water as medium is made. The reason for this is to see if there are any leakages and that everything runs smoothly. This test will be performed in Eskilstuna instead of on site to be able to quickly modify or repair parts. The test documentation can be viewed in the appendix.

Second test
This test will be performed on site with wet air, steam and the hygroscopic solution. The equipment will have a slow start to see if everything works as it should. This test is just to verify the equipment is ready for evaluation and therefore no specific test are performed. The pressure drop over the columns will be measured so that future values can be compared. The meaning with this is to detect if any crystallization in the equipment has occurred.

5.6.2. Test of performance

Regeneration and condensation
The capacity of the regeneration will be determined by closing the valve to the hygroscopic absorption and measuring the concentration at different times. This gives a function where the derivate will give the capacity for each concentration of potassium formate. These values will be compared to the amount of steam consumed at the other side of the heat exchanger by measurements of the condensate. The difference in energy will show any eventual losses and indicate any faults.

The same idea is used in the condensation step, where the condensate will be measured and then compared to the number for the transferred energy to the VVG system. To be able to measure the condensate, the condensate in the regeneration is measured first and then subtracted from the total flow of condensate.

Hygroscopic condensation
The humidity of the air in to the hygroscopic condensation can be calculated by combine the amount of vapor from the ordinary condensation and the assumed amount of vapor in the wet air inlet. This together with measurements of the humidity in the outlet will show the number of transfer units for the column. The amount of absorbed water will be measured in the same way as in the regeneration. This will, together with the temperature difference of the wet air, give the amount of energy extracted. The absorbed energy will be compared with the energy transferred in the heat exchanger to see if there are any losses or faults.

Heat exchanger to district heating
The temperature will be measured in all flows to and from the heat exchanger. This will show the driving force at both ends which in turn will show if the transfer surface is enough.
Internal heat exchanger
As in the district heating heat exchanger, the temperature will be measured in all flows to and from the heat exchanger. The driving force at the ends will show if the heat exchanger has the right transfer area.

Total
When the equipment is switch off for a long period, it is practical to dilute the formate solution to between 50 and 60 w% where it will not freeze. The time from start to when the equipment is working as normal will be measured. This is done by diluting the solution, maximizing the steam flow and measuring the time until the concentration is close to under normal conditions. The reason for this test is to know if it is feasible to use this type of system at regular basic. It will also be noted the time needed to heat up the equipment to the running temperature. Due to that factors as the outside temperature and the amount of liquid in the equipment affect this time, it will only be noted as a guideline for what to expect.

6. Results

6.1. Stream data from Holmen

Table 4: Key values from equipment

<table>
<thead>
<tr>
<th>Wet air to equipment</th>
<th>Temperature (dry)</th>
<th>140-168°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet bulb temperature</td>
<td></td>
<td>20-65°C</td>
</tr>
<tr>
<td>Wet air after equipment, (the lowest values achieved)</td>
<td>Temperature</td>
<td>65°C</td>
</tr>
<tr>
<td></td>
<td>Wet bulb temperature</td>
<td>40°C</td>
</tr>
<tr>
<td>District heating (VVG)</td>
<td>Cold temperature</td>
<td>65-70°C</td>
</tr>
<tr>
<td></td>
<td>Hot temperature</td>
<td>81°C</td>
</tr>
<tr>
<td></td>
<td>Produced effect</td>
<td>280 kW</td>
</tr>
</tbody>
</table>

6.2. Regeneration
A number of tests have been done with the regeneration. Unfortunately, the original pump (PVDF, magnetic drive) could not handle the fluid all the time. This was partially solved by throttling the flow by a valve and made the pump work for a little bit longer periods. A new pump in stainless steel was finally installed and later used during the last four tests. The test data are shown in figure 15:

In the tests, there is shown that the regeneration is working. The measurements show a tendency with less evaporation at higher concentrations, but due to too few measurements and too much variation between tests, no values for this decrease are published. The values also show that the evaporation will be below the predicted range.
The highest average rate of evaporation was 0,089 kg/s (in test run 6) and the total average for all tests were 0,054 kg/s. This is below the calculated rate (just above 0,1kg/s). However, as seen in Figure 13, the margin of errors in the measurements is significant and the values should not be used for future calculations. If all values are managed together though, a trend is forming. To verify this, more tests needs to be done.

The driving force in two of the tests can be viewed in the following table. All values from the tests can be seen in appendix.

<table>
<thead>
<tr>
<th></th>
<th>designed values</th>
<th>10-june</th>
<th>14-june</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{air in}}$ [°C]</td>
<td>161</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>$T_{\text{air out}}$ [°C]</td>
<td>120</td>
<td>122</td>
<td>125</td>
</tr>
<tr>
<td>$T_{\text{dew point condensation}}$ [°C]</td>
<td>70</td>
<td>71</td>
<td>67</td>
</tr>
<tr>
<td>$T_{\text{dew point}}$ [°C]</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$F_{\text{condensate}}$ [g/s]</td>
<td>88</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>$T_{\text{hygroscopic force}}$ [°C]</td>
<td>47</td>
<td>38</td>
<td>43,5</td>
</tr>
<tr>
<td>$T_{\text{out}}$ [°C]</td>
<td>7,54</td>
<td>28,0</td>
<td>25,4</td>
</tr>
<tr>
<td>$T_{\text{in}}$ [°C]</td>
<td>32</td>
<td>41</td>
<td>35,5</td>
</tr>
<tr>
<td>$T_{\text{in}}$ [°C]</td>
<td>16,9</td>
<td>34,1</td>
<td>30,2</td>
</tr>
</tbody>
</table>

Figure 13: Test runs 3 and 4 were made with a low flow of both steam and hygroscopic solution. Test run 5 was made with maximum steam but a slow formate flow. Test run 6 was done with a slow flow of formate but with warm equipment. 2 and 3 was made with maximum flow of air and steam.

Figure 14: Temperature difference used for mass transfer. The number 2 indicates the position between the regeneration and condensation. The dew point in point 2 is calculated through a mass balance.
The $\theta_{in}$ value is calculated as if the hygroscopic force equals the one in the inlet. This is not true due to the concentration of the liquid through the column. Unfortunately, the flow of potassium formate is difficult calculate due to the flow between the columns and because there is no flow meter. The real $\theta_{in}$ value should therefore be lower than it is shown here. However, the needed temperature difference is still very large compared to the transferred energy. This is obvious when they are compared to the value from the designed version. There are two possibilities of why these numbers are so large. In the first case, the film gives a much larger resistance to mass/heat transfer than expected. This can be solved by increasing the potential in form of temperature difference by for example increasing the steam temperature or lower the hygroscopic effect by lowering the concentration. In the second case, the transfer area is too small. This could be due to too low flow of formate and due to that, bad wetting rate. It could also be due to a large formate flow. This might give evaporation inside the film which would result in loss of film. To investigate which of these cases that are the major problem, the formate flow may be changed and then compared with the condensate from the condenser. At the same time, the potassium formate can be diluted with the steam condensate to see if the evaporation increases at lower concentrations. The wetting of the regeneration can also be controlled by ocular means from the top of the column.

The amount of steam used depends on the amount of evaporated water. The steam has no automatic valve and if the process is stopped there will still be some steam consumed. The amount where measured to 1,23ml/s. This means just below 3 kW heat losses.

6.3. Hygroscopic absorption

Due to the short possible time to regenerate the hygroscopic solution and that the hygroscopic column needed to have a flow for cooling, no tests could be done with concentrations above 60 w%. At 60 w% and at 70°C the boiling point elevation is about 16 °C. This means the only vapor which can be condensed is the one between 54°C and about 60°C.
Figure 15: Test results from hygroscopic absorption using low concentration of potassium formate compared to the optimum one.

Figure 16: Test results from concentrations below of what the equipment is designed
The highest average rate of absorption for these tests was 0.0068 kg/s. The test “no 2” was unfortunately done during a period when the paper machine did not produce any paper. This result in a high temperature with a very low humidity and the absorption started to regenerate. During the time for the measurements there were frequently recurring shutdowns of the paper machine. This may have affected the measurements.

All planned tests of the hygroscopic column as a single unit were aborted and instead the tests were done together with the other equipment. The result for these tests can be seen underneath the headline: In total

6.4. Condensation
The ordinary condensation has been working well. The temperature has been lowered from just above 120°C to 70°C and the VVG temperature has been raised from about 68°C to 80°C. This gives a driving force of 2°C at the cold side which is very good.

6.5. Heat exchangers

6.5.1. VVG heat exchanger Ex-1 (Absorber circuit)
The tests show that the heat transfer is much lower than designed. The temperature difference between the two sides can be viewed in Figure 17.

<table>
<thead>
<tr>
<th>Försök</th>
<th>Temperatur VVG</th>
<th>Temperatur formiat</th>
<th>℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74</td>
<td>80</td>
<td>6</td>
</tr>
<tr>
<td>08-jun</td>
<td>68</td>
<td>74</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P [kW]</td>
<td>70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Försök</th>
<th>Temperatur VVG</th>
<th>Temperatur formiat</th>
<th>℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>77</td>
<td>84,5</td>
<td>7,5</td>
</tr>
<tr>
<td>10-jun</td>
<td>65</td>
<td>74,6</td>
<td>9,6</td>
</tr>
<tr>
<td></td>
<td>8,51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P [kW]</td>
<td>123</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Försök</th>
<th>Temperatur VVG</th>
<th>Temperatur formiat</th>
<th>℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>77</td>
<td>85,5</td>
<td>8,5</td>
</tr>
<tr>
<td>13-jun</td>
<td>65</td>
<td>74,4</td>
<td>9,4</td>
</tr>
<tr>
<td></td>
<td>8,9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P [kW]</td>
<td>110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Försök</th>
<th>Temperatur VVG</th>
<th>Temperatur formiat</th>
<th>℃</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>77</td>
<td>85</td>
<td>8</td>
</tr>
<tr>
<td>14-jun</td>
<td>58</td>
<td>72</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>10,7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P [kW]</td>
<td>140</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 17: Temperature difference in VVG heat exchanger where \(\theta_m\) is the mean value and \(\theta_{lm}\) is the logarithmic mean value

The large heat exchanger is not working in a good way. The transferred heat is much lower than the values it is constructed to maintain. For example should the heat transfer in the fourth test be above 1000kW instead of 140kW as in this case. The reason for this must be that transfer area is blocked or that the heat transfer coefficient is decreased due to a coating made
by eventual dirt. No coating has been seen in the density measurements and therefore it is likely that some kind of dirt from the building is blocking channels in the heat exchanger. Therefore it should be opened and cleaned and later tested to see if the problem is solved.

6.5.2. Hygroscopic circulation heat exchanger Ex-2
The temperature indicator at the last position (TI-20) was not able to give any values. To know the last values an assumption were made that the mass flow of potassium formate is equal on both sides of the heat exchanger and that the concentrations are 73 w% respective 77 w%. The results can be viewed in Figure 18.

<table>
<thead>
<tr>
<th>Hygroscopic circulation heat exchanger</th>
<th>T to regeneration</th>
<th>T from regeneration</th>
<th>θlm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Varm</td>
<td>121,45</td>
<td>123,15</td>
</tr>
<tr>
<td>08-june</td>
<td>Kall</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>?</td>
<td></td>
<td>2,</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Försök</th>
<th>T to regeneration</th>
<th>T from regeneration</th>
<th>θlm</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Varm</td>
<td>114,14</td>
<td>118,39</td>
</tr>
<tr>
<td>13-june</td>
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<table>
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<th>T to regeneration</th>
<th>T from regeneration</th>
<th>θlm</th>
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<tr>
<td>?</td>
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Figure 18: Temperature differences in heat exchanger Ex-02 where θlm is the logarithmic mean value

The small heat exchanger is difficult to evaluate. This is due to that the mass flow and the transferred energy through it is unknown. If only the temperatures are taken into account, the driving force seams a little bit large. This is not surprising though; the heat exchanger is designed for another project. However, the temperature gradient was not extremely bad and the escaped heat from the regeneration was lowered.

6.6. VVG-pump
The present pump capacity is up to 22 m3/h at approximately a differential pressure at 3 bar (1,5 bar to 4,5 bar). If the pressure gradient is lowered to 2 bar, the flow may be increased to about 60 m3/h. The pump has been working smoothly apart from one problem. The pressure in the process water net is unstable, both in absolute pressure but also in differential pressure. This together with that there are no check valves, and therefore the flow may be reversed when the pump load is too low. This may result in a problem in the logic system. The needed frequency for the pump to achieve a flow in the right direction is about 40 Hz (This varies due to a varying pressure difference in the VVG-net). The logic system controls the pump by lowering the frequency if the temperature is below 81°C. If the speed gets too low, the flow
might reverse and the temperature will reach the hot side of the VVG-net. In this case, the temperature is close to 80°C, and therefore the pump will keep its speed the backflow will continue. This could be solved by using the energy meter to measure the flow or by leading the produced hot water to the VVG return pipe instead of the VVG output pipe. This would give the same pressure at both sides of the equipment and due to this, no backflow would be possible.

6.7. Hygroscopic pumps
The pump has been working well, but there are some risks for the future. First, the impeller of pump “P-004” is constructed for solutions with a density below 1200 kg/m³. In the calculations, the concentration in the hygroscopic column should be above 70w% which means a density of more than 1500 kg/m³. Second, the pumps cannot handle temperatures above 85°C, and this is done regularly. Third, the pumps use magnetic drive and are sensitive to particles which are very bad due to the risk of crystallizing of hygroscopic solution. Due to these reasons, the pumps may be exchanged in a near future, especially if the equipment is to be used by remote control.

6.8. Regeneration pumps
The regeneration pump did work satisfying in the first couple of tests with water and cold potassium formate. When the process was tested at higher temperatures the pump load suddenly dropped to zero and was immediate switched off. The pump had problem to start afterwards, even though the temperature had decreased. Since the first problems there have been troubles regularly. Due to suspicions that the high temperature together with the low concentration was creating the problems, a valve on the pressure side of the pump, was partially closed. However, due to all these problems, a new stainless steel pump was installed with the result of a much better reliability.

6.9. In total
Four tests were done with the whole equipment. In total the equipment delivered about 3MWh during these tests. Warm up time has not been measured because it reaches this temperature within minutes after start. The time until the equipment reaches steady state has not been measured because it depends on many factors and it may take up to a couple of hours if the conditions are not favorable.

Figure 19: Achieved values from tests with the whole equipment. More values can be viewed in appendix

The values show that there is an effect made by hygroscopic solution. The dew point has been lowered from about 60°C to 47°C with an outgoing dry temperature of 77°C. This means that the temperature performance works almost as calculated. The reason it do not reach all the way is because the VVG heat exchanger not been able to lower the temperature of the potassium formate enough and that the VVG temperature is 5°C warmer than designed for. The heat exchanger did not transfer the designed heat either and therefore a poor capacity was achieved.

Another part which must be optimized is the use of a too large airstream through the regeneration. The difference between the inlet dew point before the regeneration (60°C) and
the outlet dew point after the condensation (70°C) will get evaporated and later absorbed in the hygroscopic column. This amount will get transferred between the parts and consuming the same amount of steam as it delivers in the hygroscopic column. This means it will lower the COP. If the air stream would to be reduced, the dew point in the regeneration air would increase and by that making it possible for the condenser to use a larger part of the vapor. The same problem occurs when the flow between the regeneration and the hygroscopic column is larger than necessary. This gives a lot of heat from the regeneration escapes with the potassium formate. The heat may be regained in the VVG- heat exchanger, but the higher temperature gives less amount of vapor which may condense by hygroscopic power which in turn lowers the total captured energy.

7. Discussion of remaining equipment

7.1. Hygroscopic heat pump versus other sources
This choice is not always obvious. The cost for the electric heat pump is higher, and the cost for electricity higher than for low pressure steam, but the COP is almost twice as high with an electric heat pump. If there is cheap low pressure steam, or if the wet air stream contains enough heat to handle the regeneration by itself, the hygroscopic heat pump is unbeatable. However, if the heat needed to regenerate the hygroscopic solution must be produced for this reason only, the choice is leaning towards the electric heat pump. This means that the hygroscopic solution is preferable at applications as power plants, paper mills and other industries with very much low pressure steam or hot air flows available. At other applications as wood dryers, the answer is not as easy.

7.2. Piping and tanks
The system could work by itself today but there is some parts that must be more looked into to be certain nothing gets damaged.

First, there is a risk that the vapor pressure suddenly drops in the wet air. This may occur when the paper machine stops the feed of paper. Then no water can be taken from the wire, and therefore, no vapor can be transferred to the hygroscopic condenser. The risk with too low vapor pressure in the equipment is seen in “Test run 2”, when the absorption starts to work as regeneration. This means the hygroscopic solution will be more concentrated and, if not stopped, crystallize.

The margins are also too small between the highest surface level and the pump inlet. When the pump start to work, the amount of solution which holds up in the column and pipes, are so large the amount in the tank might not be enough. In this equipment the problem is temporally solved by an additional tank next to the column. This configuration is working better, but there is still a need for redistribution of hygroscopic solution at start and stops. If the equipment is to be used by remote control, it is important to increase the capacity of the tank. The same problem occurs when the equipment is turned off. If the fluid needs to be diluted, there is no room for the extra volume in the tank. This gives potassium formate might escape into the bypass fan through the air inlet pipe. This could be solved by increasing the volume of the existing tank or by adding an angle to the inlet so that formate can stay in the pipe until
the pump are restarted. Today, a temporary solution is a valve at the bottom of the fan where the formate can flow out into a bucket. This needs to get improved with a better type of holder and water seal of better quality. In the future, this should be solved by the use of a larger tank with better margins.

The float valve should be placed at a higher position in the tank. The level which the valve gives is very close to the level guard and if there become any waves in the tank, these would probably turn the equipment off.

To summarize, in future equipment, it is recommended to use larger tanks with larger margins between the parts.

Extra valves at the bottom of the columns are needed so that the fluid can be escaped without any leakages with the loss of potassium formate as a consequence.

The hygroscopic solution crystallized after some of the experiments when the liquid was cooled down. This could be solved by the problem mentioned in the part “Safety against crystallization”, and the one which has been used during tests is to dilute the solution. However, to avoid polluting the solution while using water from the local distribution net with substances as calcium, a tank should be installed which collect the condensate. When at risk for crystallization, the solution can quickly and easily be diluted to a concentration which can handle lower temperatures. The solution must be executed together with an increased volume of the tank in the hygroscopic column so that the volume can handle the extra water.

### 7.3. Container

Design the equipment in a way which minimizes the leakage into the container. For example it is important that all pipes which will be attached should be inclined towards the container. In this way water flowing along with pipes into the container could be avoided. This is important due to that if the insulation gets wet, the heat transfer through it would increase and the idea of it would be spoiled.

The design today makes the temperature in the container quite high. As example, the variable-frequency drives have been working at temperatures above 40°C during some experiments. Some of the parts in the electronics can’t handle these high temperatures and will work slowly or, in worst case, not at all. Therefore it is important, if the equipment is going to be remote-controlled, to place the sensitive parts outside the container or make a cooling device which can handle to remove the heat in the surrounding air.

The only drainage today is drilled holes into the floor. This is important if there becomes any leakages and for the cleaning of the container. If water or especially hygroscopic solution lies on the floor, it will corrode and might get damage after a while. If the level gets high enough, the pumps will be at risk.

### 7.4. Electronics and the logic system

The whole system is today controlled by a touch screen on sight. This could be changed in a quite easy way by installing an internet connection (which is already prepared for) and using a computer on sight or off sight to control everything. To do this, an interface must be created which handles the programming languish in the electronics (in this case: Modbus TCP).

The guidance for the VVG pump must reprogrammed. When the temperature is below 80
the pump should decrease its number of revolutions which works perfectly. The high pressure difference between the inlet and outlet to the VVG makes the water leak backwards through the pump at low speeds. This gives that if the speed is below this certain limit and the water is flowing backwards, the temperature will equal the temperature of the VVG, which is about 80°C. massimo the pump maintain its speed, which means the reversed flow will proceed. The logic system will be captured at this temperature. This problem is difficult to solve due to a varying pressure difference which makes it impossible to decide a minimum number of revolutions. During the tests, the speed was adjusted manually. It might be possible to use the heat meter and connect it to the guidance, but this might be complicated. Another solution could be to use the equipment to preheat the VVG-water before the boiler. This means water will be taken and added to the same pipe which results in that the pressure difference will equal only the losses. This means backflow will not be possible and in this case, the guidance would be better suited.

8. Conclusion
During the initial tests some problems have been discovered. Some are already solved but there are still many to solve. However, in total the experiments show that the hygroscopic effect works. The temperature performance has been good with the lowering of the dew point from about 60°C to 47°C at an outgoing dry temperature at 77°C. The heat has increased the temperature of the process water from 65°C to about 80°C. The capacity has not been as good due to problems of transferring heat through the VVG heat exchanger. At the last test 280 kW was delivered whereof 46 kW from condensed vapor and 105 kW from steam. The last 129 kW was from the sensible heat in the incoming humid air. In total the equipment has been delivering about 3 MWh during about 15 hours of use. These values are below the predicted, and the equipment does obviously need to get optimized and many parts need to get adjusted. However, the equipment has showed the hygroscopic effect is working and even exceeding the expectations concerning the lowering of dew point and that the process seems to be a good choice of arrangement for this type of application. The adjustments will be done during the summer (year 2011) and the equipment is to be in continuous use during the autumn (year 2011).

8.1. Future theoretical studies
There are many things to discuss and measure in the future. First of all, more experiments must be performed with the equipment. This, to know if the equipment will work as well as the theoretical ideas and calculations indicated on.

The Marangoni effect is important to look more into. As mentioned before, additives is used in refrigeration machines with a good effect and therefore it is trustworthy it could help the process in the reverse. Also the temperature can change the surface tension and therefore is can be interesting to try to transfer heat in an irregular pattern in the heat exchangers.

Together with the Marangoni effect it could be interesting to look more into the effect of wave laminar streaming and its dependence of the Reynolds number. This could help to optimize the construction of the heat exchangers in the equipment.
As mentioned before, ultrasonic vibrations help the mass transfer from the liquid phase to the gas phase. The report do not mention or conclude if any other wavelengths could help the transfer, and therefore it would be interesting to see if the vibrations from a paper mill or any other equipment could be enough, to increase the efficiency of the transfer. As example, it could be interesting to see if the placement on the ceiling above the paper machine gives a better transfer than if the container would be placed next to it on the ground.

Which type of steel that can be used? Due to time limit of this report, the time will not be enough to with certainty say the test sample of steel can handle the environment or not. To do this, as much time as possible is needed. The more time, the easier an eventual effect on the sample will be spotted. If steel of quality 304 could be used instead of the one with quality 316, around 20% of the material costs could be spared.