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TNO report

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Sorption based heat recovery in drying process

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1 Summary

Drying is an essential operation in the chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral processing, and wood processing industries. The removal of the liquid from the product is a very energy-intensive process: about 15% of the industrial energy use is for drying purposes. This accounts for 90 PetaJoule (25TWh) per year within the Dutch industry.

Convective drying is the most commonly applied drying technology and typically use heated air to achieve drying. This process results in moist, lukewarm air that contains large amounts of latent heat in the form of water vapour, which is lost through the exhaust. Recovery of this latent heat comes with many practical challenges, such as pollution or fouling by sticky particles, and therefore the lukewarm, moist air is commonly vented to the atmosphere.

By applying a sorption process, the latent heat in the humid air can be recovered while avoiding fouling and stickiness issues. The moisture is absorbed by the sorbent, resulting in dry air and the heat of adsorption will heat the air to be re-used in the drying process.

The objective of the IDEA project (**I**ndustrial **D**rying **E**nergy-efficiently using **A**bsorption) is to demonstrate the technical and economic feasibility of the liquid sorption concept by demonstrating the liquid sorption technology under conditions typical for drying applications in industry. The activities performed in the IDEA project have led to an increased knowledge and operational experience, applying liquid sorption for latent heat recovery of humid air.

A new process model was developed to study liquid sorption drying processes with a variety of sorbents and operating conditions. The use of highly concentrated phosphoric acid as a strong liquid sorbent was selected for further analysis and pilot testing under simulated industrial air drying conditions.

Experiments on a pilot scale liquid sorption setup, operated by Qpinch under simulated industrial drying air conditions, were successfully performed and generated results for validation and tuning of the phosphoric acid system model of Qpinch. The tests have demonstrated the technical feasibility of the proposed sorption drying process.

System simulations and performance analysis were done on different process integration schemes and operating conditions, to identify the options with the highest energy saving at the lowest complexity and cost. The energy saving potential for this concept was in a broad range of 85-20% depending on the scale of air handling and type of system integration. The integration scheme that resulted in 39% energy saving, was elaborated to calculate the CAPEX and analyse the economic feasibility. A simple payback time in the range of 4-6 years was calculated.

Technical challenges to be addressed in further developments and future upscaling should address the validation of the packed bed absorber concept, and a further increase of the temperature of the liquid sorbent regeneration stage.

2 Background and objectives

Industrial Drying processes
Drying is a process where a liquid, usually water, is removed from a solid. This process is often used as a final step before finishing the product. Drying is an essential operation in the chemical, agricultural, biotechnology, food, polymer, ceramics, pharmaceutical, pulp and paper, mineral processing, and wood processing industries. The removal of the liquid from the solid is a very energy-intensive process: about 15% of the industrial energy use is for drying purposes. This accounts for 90 PetaJoule (25TWh) per year within the Dutch industry. Drying processes not only require large amounts of energy, they also are very critical with respect to product quality.

There are different drying technologies, depending on the application. In general, drying technologies can be categorized into:
- *Convective drying* – air is used for providing heat for drying and for the removal of the released moisture. Spray drying is a typical example of convective drying.
- *Contact drying* – air is used for removal of moisture whereas the heat for drying is provided through a surface. Papermaking is a typical example of contact drying.
- *Radiation drying* – heat is provided using radiation. Infrared drying is a typical example of radiation drying.

Convective drying is the most commonly applied drying technology. The drying conditions, such as air temperature, humidity and flow rate, and residence time are optimised to achieve the required product quality. Convective drying processes typically use heated air to achieve drying. This is an adiabatic process resulting in moist, lukewarm air. This air contains large amounts of latent heat in the form of water vapour, which is lost through the exhaust.

Energy efficient drying: In theory this latent heat can be recovered through condensation by cooling down the air below its dew point. In practice, the temperature of the recovered heat of condensation is too low for useful application, and condensation is often not possible due to risks of pollution or fouling by particles that can become sticky under such condensing conditions. Therefore the lukewarm, moist air is commonly vented to the atmosphere.

Problem statement
To regain latent heat of the exhaust air of drying processes and increase the energy efficiency, the problem that should be solved here is to recover and reuse the waste heat of the outgoing moist air at a higher temperature level, without affecting the production process and product quality. Conventional (latent) heat recovery using condensation of moisture from the exhaust air is unsuitable for many drying applications due to fouling problems or agglomeration of particles. Alternative methods are required to recover the latent heat in the convective dryer exhaust air.

Sorption drying
By using a sorption process, the latent heat in the air can be recovered without having to pass through the stickiness zone of the dried powder. The moisture in the air is absorbed by the sorbent, resulting in drier air, heated by the heat of

absorption. The heated dry air can be re-used again for drying. *Figure 1* shows a typical industrial convective dryer (spray dryer) conceptually combined with a liquid sorption unit. The amount of heat supplied in the sorption system is similar to the conventional stand-alone spray dryer, however the regenerator of the sorption system yields an additional flow of steam, which can be used elsewhere on-site.

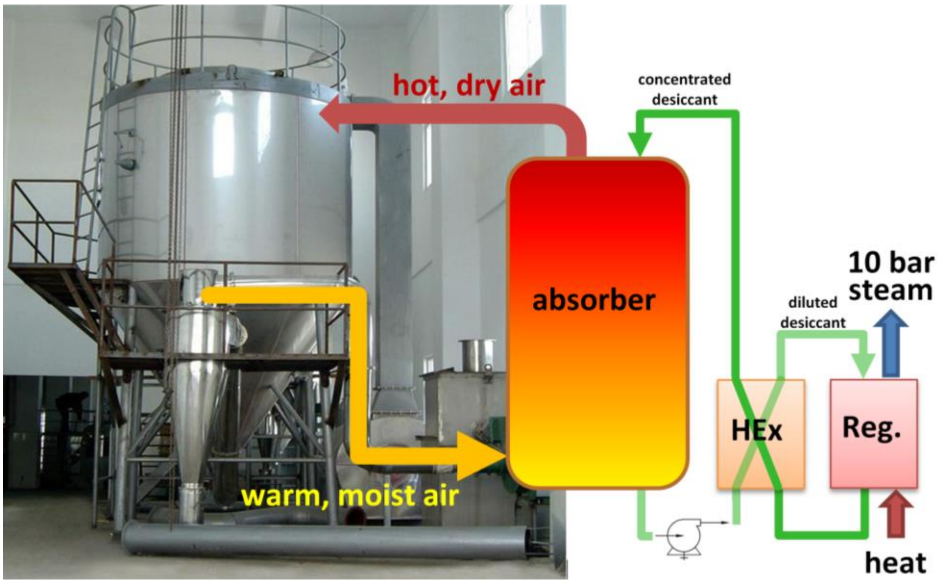

Figure 1: Industrial spray dryer (left) schematically connected to a liquid sorption unit (right).

Liquid sorption

Where in a conventional drying unit the exhaust air is vented to ambient, in the proposed liquid sorption system, this warm, moist air is fed into the absorber unit. In the absorber unit, the exhaust air meets the liquid desiccant in counter flow. The liquid desiccant absorbs the moisture from the exhaust air whilst releasing the heat of sorption. As a result, the air leaves the absorber at high temperature and low humidity. The diluted liquid desiccant is subsequently led to regeneration unit where the absorbed water is converted into steam which can be used in the drying process or elsewhere on-the production location. The sensible heat losses can be minimized by using liquid-liquid heat exchangers. No air is trapped and pollutions can be filtered out if necessary.

In the forerunner EELS[1] project, such a liquid sorption system was investigated. This project focused on the energy-savings potential of the sorption cycle, the liquid desiccants requirements and a first-estimate of the techno-economic feasibility of the concept. The publications[2,3,] of the EELS project show the liquid sorption cycle has the potential to recover 60 to 100% of the drying energy in the form of (mainly) medium pressure steam. Phosphoric acid (H_3PO_4) was identified as preferred liquid desiccant. These results were all based on model calculations and small lab scale tests on the absorption step.

[1] Joint Industry Project funded by the Ministry of Economic Affairs with reference number TEEI314007.
[2] “Study on advanced drying concept shows more than 58% energy savings potential in spray drying applications”, ISPT Newsletter January 2017.
[3] “Heat recovery in milk powder drying by using a liquid sorption process”, Diego Pineda Quijano, Michel van der Pal, Carlos Infante Ferreira, Robert de Boer, Jasper Vollenbroek, Proceedings of 12th IEA Heat Pump Conference 2017, Rotterdam.

Project goal and activities
The goal of the IDEA project is to demonstrate the technical and economic feasibility of the liquid sorption concept by demonstrating the liquid sorption technology under conditions typical for drying applications in industry.
The activities in the project are targeted to design, build and test a bench scale absorption unit, capable to increase air temperature by at least 50°C from dryer exhaust air conditions and absorbing at least 30 gram H_2O per kg air. The capacity of this bench scale unit will be several kg of water absorbed per hour which is equivalent to several kW of energy.

Furthermore, based on the bench scale characteristics and performance, a full-scale design of a liquid sorption system is made, to assess the techno-economic feasibility of liquid sorption drying.

These results will form a necessary step in the further development of liquid sorption for drying purposes.

3 Results

3.1 Liquid sorbent selection

Starting point in the selection of potential liquid sorbents is their ability to absorb moisture at increased temperature levels. From thermodynamic perspective the sorption strength of any sorbent decreases with increasing temperature, and therefore sorbents with very high sorption strength are needed in the targeted drying applications.

Typical liquid sorbents that can fulfil these requirements are found in the group of strong acids and strong bases. Examples for these are sulfuric acid (H_2SO_4) nitric acid (HNO_3) phosphoric acid (H_3PO_4) sodium hydroxide (NaOH) These acids and bases must be applied in highly concentrated solutions to keep their sorption strength at the required high operating temperatures.

Working with strong acidic solutions puts challenges on the regenerator side to apply corrosion resistant construction materials that can withstand the high temperatures, needed to regenerate the sorbent and generate useful steam quality for the industrial site.

Sodium hydroxide also needs corrosion resistant construction materials but has an additional challenge to prevent crystallization of highly concentrated solutions. It also reacts with CO_2 in the air, which will lead to the formation of carbonates, which will precipitate.

Phosphoric acid (PA) was selected as the preferred liquid sorbent, as it has the required sorption strength to dry humid air at the desired high temperatures.

3.2 Model development

In order to develop a good understanding of the process conditions to operate a liquid sorption drying system a model was developed which can simulate a range of operating conditions for the liquid sorption system, connected with various drying air conditions.

This model is built using the Dymola and TIL suite software packages as modelling and simulation environment, based on the Modelica modelling language. It uses a library of thermal components, allowing to do stationary and dynamic modelling of thermal systems, as well as library of thermophysical properties of materials, such as the liquid sorbents in the current system. Figure 2 shows an overview of a generic liquid sorption system model connected to a drying air circuit. The main components and circuits are indicated.

The model allows to vary the air inlet conditions, the type of liquid sorbent and its operating conditions, in order to study the drying capacity, the energy balances and overall energy efficiency of the process.

The heat and mass transfer rates in the absorber are the parameters that strongly influence the modelling results. These parameters are decisive in how much water vapour will be absorbed and how much heat will be exchanged between air and liquid sorbent and how much exchange area should be included in the absorber.

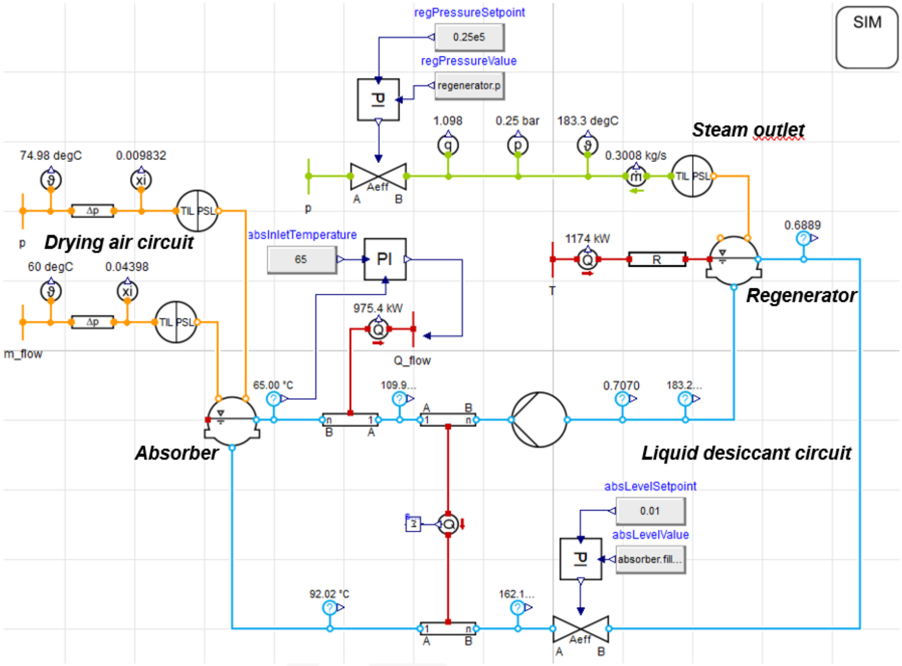

Figure 2: Overview of the generic liquid sorption model used to study the air drying and heat recovery application.

The company Qpinch from Antwerp, Belgium develops industrial heat recovery and re-use technology based on phosphoric acid as working fluid in their heat transformers. Qpinch uses their proprietary process simulation tool (based on Aspen) to design their heat transformer systems for various applications. This simulation tool was applied in the IDEA project to study working conditions for the phosphoric acid cycle in this innovative open sorption drying concept. The result of the Aspen modelling allowed to compare with the more generic TIL suite based liquid sorption model and to have a first estimation of the heat and mass transfer rates to be applied in the absorber.

3.3 Prototype development

The Qpinch technology and knowledge on the use of phosphoric acid in sorption processes was further connected to the IDEA project. Their facilities allowed to develop the bench scale prototype and to perform technical feasibility studies on simulated air drying conditions.

Starting from a previous prototype system, modifications were made to allow for ‘open sorption’ operation. An air conditioning step (temperature and humidity) was included to simulate the dryer exhaust conditions. This air was exposed to a flow of concentrated phosphoric acid in the counter current absorber or ‘drying column’. The regeneration of phosphoric acid was done one an existing regenerator column, heated by steam.

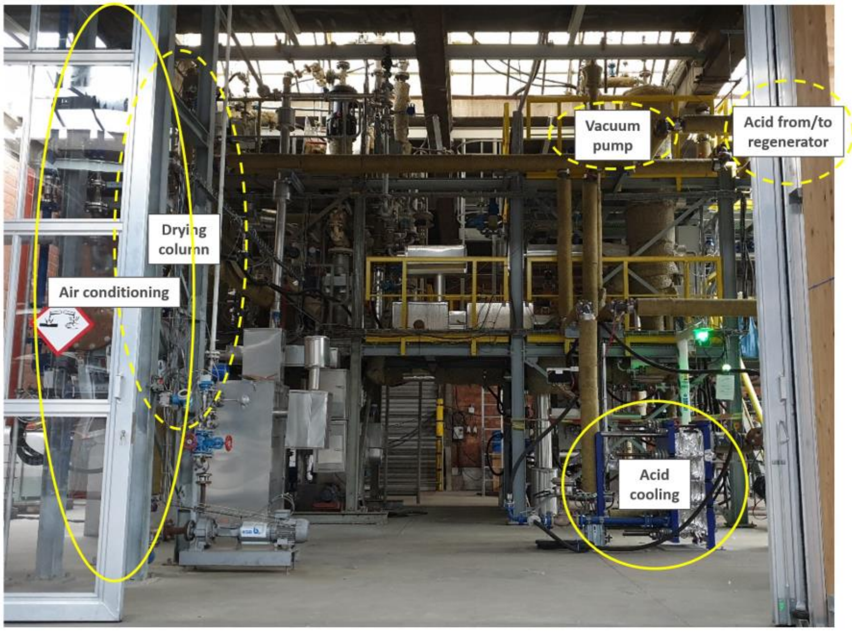

Figure 3: Overview of the pilot test setup for the absorber test (© Qpinch).

The pilot systems is equipped with flow, temperature and humidity sensors and control systems to allow continuous operation and measurement under the targeted process conditions

3.4 Performance tests and Qpinch model validation

3.4.1 Experimental program

A set of 11 specific test conditions was applied on the absorber column with variations in air flow rates, humidity levels, liquid phosphoric acid flow rate, variations in phosphoric acid inlet concentration and inlet temperature. Over the test program, an incoming absolute air humidity up to 80 g/kg was applied with exiting moisture content showcased as low as 8 g/kg dependent on the parameter setpoints.

The results of the base case test condition were used to directly compare with the existing phosphoric acid system model (model 1) and more importantly also used to tune the mass transfer rate of the absorber model, in order to obtain a representative fit between the experimental results and the model (model 2).

3.4.2 Model validation

Several test cases were defined, performed and process simulations were made in Aspen based on both the model 1 and model 2 to study the results. A first goal is to assess how close the test results approach the simulation results of model 1 for all studied parameter variations. Secondly, the absorption kinetics of model 2 are modified to copy the results as obtained in the base case test-run. It is interesting to study if model 2 stays accurate imposing all parameter variations as executed.

Two additional parameters will be used during the discussion of the model validation:
1) The moisture removal efficiency (MRE):

$$MRE\ (\%) = \frac{AHin - AHout}{AHin}$$ AH = absolute humidity of air

2) The mean absolute percentage error (MAPE) used to quantify the error between the simulation and actual experimental results. Within the formula, the MRE values are implemented as it represents the overall drying capacity of the absorption unit:

$$MAPE = 100 * abs((MRE_{exp} - MRE_{sim}) / MRE_{exp})$$

An overview of the deviations between the experimental results and the model predictions is plotted in Figure 4. In this figure the deviations for all 11 test cases are plotted for each case as MAPE values (%). In blue and orange are the errors shown for respectively the fitted (model 1) and tuned models (model 2).The outliers in the comparison are observed for extreme conditions with very high air flow rates and for very low phosphoric acid flow rates, reducing the wetted area in the absorber unit.

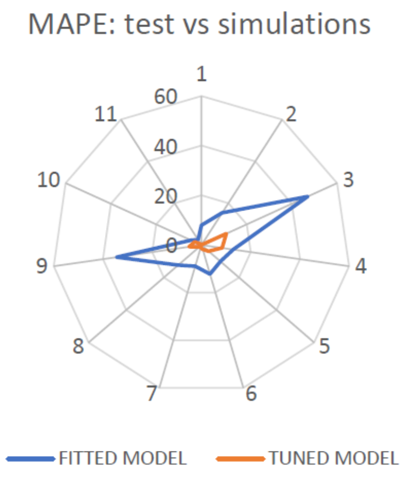

Figure 4: Plot of the MAPE values plotted for model 1 (blue) and model 2 (orange).

Starting from a zero error between test and the model 2 simulation for the base scenario, a satisfactory fit is observed for all cases with an error less than 10%. This indicates clearly that with the modified mass transfer kinetics in model 2, a good comparison between model predictions and test results is obtained, for a broad range of applied operating conditions.

3.5 Full scale design and economics

As starting point for the full scale design of a phosphoric acid based sorption drying system various options for system integration of the sorption system with an industrial drying process were explored. The exhaust air of a predefined example drying process was fed to the absorption tower of the sorption drying system, and dried and heated air returned to the drying process, see Figure 5.

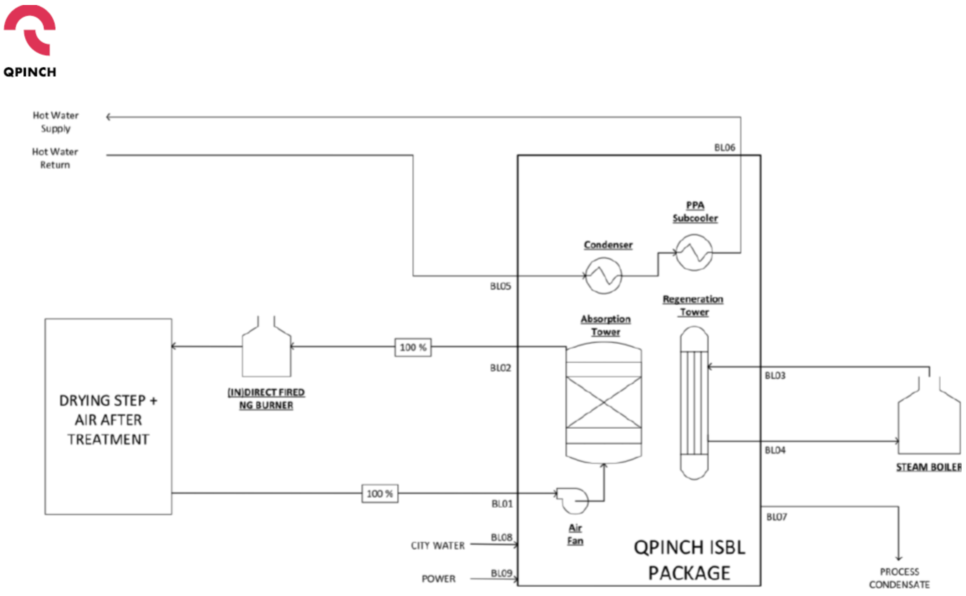

Figure 5: Basic process flow diagram for an integrated drying system.

The various integration options and operating conditions were first explored to identify the scheme with the highest energy recovery potential at the lowest cost per MW. Different from the earlier research and assumptions4, the system operating conditions, especially in the regenerator, are limited to the current design limits for temperature and pressure, as recommended by Qpinch, based on extensive operational learnings.

To increase the added value of this high temperature heat recovery by the sorption process, specific attention in the system design went into:

- Increasing the dry air temperature at the outlet of the absorption system, without compromising the required low humidity level.
- Increasing the regenerator temperature to obtain useful low pressure steam as outlet heat source.

The resulting scheme in Figure 5 is used to calculate the heat and mass balances, derive the main equipment parameters, make an ISBL cost estimate, and perform the business case analysis.

The energy balance for the reference condition and the new situation with sorption heat recovery is shown below, Figure 6, where an energy saving of 39% (2.48 MW reduced energy needs) is calculated as a result of the air drying and preheating in the sorption heat recovery system.

[4] "Heat recovery in milk powder drying by using a liquid sorption process", Diego Pineda Quijano, Michel van der Pal, Carlos Infante Ferreira, Robert de Boer, Jasper Vollenbroek, Proceedings of 12th IEA Heat Pump Conference 2017, Rotterdam.

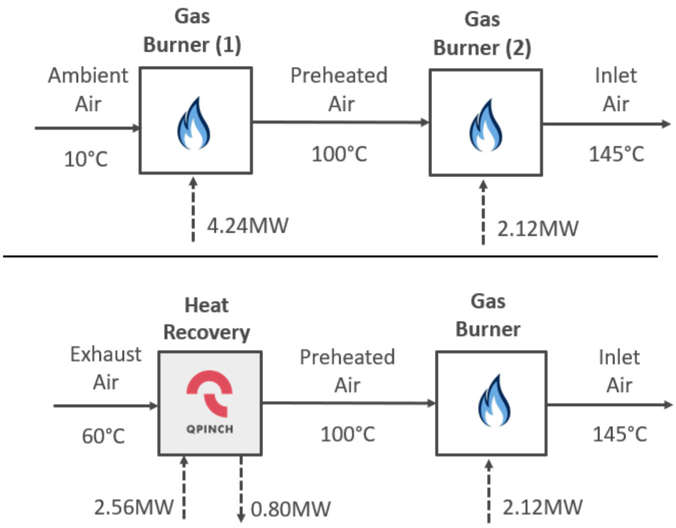

Figure 6: Comparison of energy needs to generate 145°C drying air in the reference situation (top) and in the new situation with sorption based heat recovery.

For the above condition the ISBL cost for the heat recovery system are calculated at 4.2 M€ and the total investment cost (ISBL+OSBL) are 6 M€.

The business case analysis is done based on the estimated energy savings, investment cost and operational costs. In this calculation, following assumptions were made:

- Net energy saved: 2.48 MW
- Natural gas cost: 60 €/MWh
- Electricity cost: 120 €/MWh
- ETS CO_2 price: 100 €/ton
- CO_2 intensity natural gas: 0.22t onCO_2/MWh
- Operational hours: 8322 h/yr (95% operational)
- Gas to heat conversion efficiency: 90%
- Electricity consumption: 75 kW

With these numbers, and assuming the cost estimate accuracy at ±35% the simple payback time for this system is in the range of 3.7 to 5.7 years.

3.5.1 Impact of tuning factor on simulation results

In the model validation section, a tuning factor is introduced (model 2) to align the simulation results with the measured results from the test phase. As this tuning factor was obtained at the very end of the project, the model simulations, that were obtained earlier, are all based on model 1, that slightly overestimated the system performance.

This slower kinetics result in a reduced drying performance, when keeping all other input parameters and absorber design characteristics constant:

- Outlet humidity: 17.1 g/kg (instead of 10.8 g/kg)
- Amount H_2O absorbed: 1.7 t/h (instead of 2.1 t/h)
- Latent Heat Extracted: 1.15 MW (instead of 1.44 MW)

To reobtain the desired humidity between 9-11 gH_2O/kg, the process parameters need to be optimized, e.g. changing inlet fluid parameter or tower design parameter, and an impact analysis is done on the absorber design and the overall process design, both technically and on investment cost.

The result is that by optimizing all inlet parameters (sorption flow rate/temperature/ concentration) and absorption reactor design parameters (height/diameter/packing type), it is feasible to design a performant and economical installation within the application targets. Similar characteristics are achieved compared to the base case simulation as described above.

3.6 Conclusions and recommendations

The activities performed in the IDEA project have led to a strongly increased knowledge and operational experience, applying liquid sorption for latent heat recovery of humid air.

A new process model was developed to study liquid sorption drying processes with a variety of sorbents and operating conditions. The use of highly concentrated phosphoric acid as a strong liquid sorbent was selected for further analysis and pilot testing under simulated industrial air drying conditions.

Experiments on a pilot scale liquid sorption setup, operated by Qpinch under simulated industrial drying air conditions, were successfully performed and generated results for validation and tuning of the phosphoric acid system model of Qpinch. The tests have demonstrated the technical feasibility of the proposed sorption drying process. The targeted conditions to increase air temperature by at least 50°C from dryer exhaust air conditions and absorbing at least 30 gram H_2O per kg air were achieved.

System simulations and performance analysis were done on different process integration schemes and operating conditions, to identify the options with the highest energy saving at the lowest complexity and cost. The energy saving potential for this concept was in a broad range of 85-20% depending on the scale of air handling and type of system integration.

The integration scheme that resulted in 39% energy saving, was elaborated to calculate the CAPEX and analyse the economic feasibility. A simple payback time in the range of 4-6 years was calculated.

The current temperature limitations in the absorption process and the regeneration process, have a reducing effect on the additional benefit of the sorption system in drying systems, in comparison to conventional heat recovery systems. These operating temperature limitations in absorption and regeneration need further attention to optimise heat recovery and re-use possibilities.

With the above results, and keeping in mind that economic feasibility analyses have become very sensitive to the current energy price volatility, further development of the liquid sorption drying concept is recommended. The learnings from the experimental and modelling activities indicate the following topics to be included in the future development steps:

- Modify the current absorber setup into a packed bed configuration, to enhance the performance and extend model validation.
- Focus on separately characterizing and improving the mass transfer rate of liquid phosphoric acid.
- Verify the chemical compatibility of phosphoric acid and dried product.
- Increase regenerator operating temperature to enhance the steam temperature and pressure.
- Execution of a market study to screen the different drying technologies and to assess the most interesting application areas of liquid sorption heat recovery technology.
- Assessment of integration and energy saving potential based on redesign of the dryer technology in greenfield projects (or revamp in brownfields) technology.

4 Contribution to the objectives of the subsidy program

Sustainable energy system
The intended market for the sorption heat recovery technologies is in industrial drying systems. The majority of the energy demand for drying processes is based on fossil fuels, in particular natural gas fired systems. Drying processes have a substantial contribution to the CO_2 emissions, and increasing the energy efficiency and thus reducing the energy demand will help to reduce CO_2 emissions.

The IDEA project has taken a detailed look into the energy efficiency of drying processes, with particular emphasis on the recovery and re-use of heat from the exhaust air of dryers. The model study and experimental work have shown the technical possibilities and limitations of the novel heat recovery concept. Further development needs are identified, and resolving these technical challenges in follow up activities can lead to demonstrations and commercial applications of the sorption heat recovery concept.

Knowledge development
The IDEA project has generated knowledge in the field of sorption based heat recovery technology for its use as an energy efficiency measure for (convective) drying applications. A proper balance in knowledge development in the project was obtained between the detailed thermodynamic aspects, the experimental validation, system modelling, process integration and economic evaluation. This knowledge basis is a useful source for future studies on heat recovery and energy efficiency in drying processes, as well as in other processes that have humid air as waste heat, such as flue gasses from combustion processes.

5 Spin off activities

During the project period (2017-2022) the focus of research and development has been on the large scale industrial applications. Liquid sorption based heat recovery basically allows also to perform drying processes for closed-air drying to retain and concentrate odours/aromatics. These applications, generally on a smaller scale, could provide a niche market for sorption drying, to be further explored.

The results of the current activities show sufficient potential for further investigation of liquid sorption-enhanced drying processes. Main challenges lie in rapid heat and mass transfer in the absorber and the achievable regenerator conditions, topics to be elaborated in follow-up research projects.

The modelling tools developed in this project are well suited to study and simulate alternative configurations of sorption based drying and heat recovery concepts for various liquid sorbents and a broad range of drying process conditions.

At this moment the further development of this PA liquid sorption technology for commercial applications is not a priority for Qpinch. A prerequisite is to have an interested end user involved that is willing to collaborate in the further development with investment of resources.

Once this is met, Qpinch sees the design, assembly and operation of an industrial pilot-plant on a larger scale as the next step before going to commercial scale. Results of this pilot-plant would be crucial for validation of either model 1 or 2 and to start detailed engineering.

6 Publications

No publications were made during the process.

7 Signatures

ValidSigned by Sjaak van Loo
on 2022-12-23 13:17:45

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Research Manager

ValidSigned by Robert de Boer
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