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Implementation of an Agile Manufacturing System for the Lithium-Ion-Cell-Production based on Individual Microenvironments

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Abstract

A steadily growing demand as well as changing requirements lead to a strong diversification of the current market for lithium-ion battery (LIB) cells. There are a large number of new cell chemistries for which the transition from laboratory scale to industrial production must be achieved as quickly as possible. In addition, new processes and production procedures are constantly being developed with the aim of increasing factory throughput or reducing energy consumption for example. Finally, different market segments, such as the marine or aviation industry benefit from specialized cell geometries, which are not required in mass quantities, as it is the case with available cells to date. This paper takes up the challenges outlined above and answers the question of how a production system must be designed to deal with them in the best possible way. As a result, the implementation of an agile production system for battery cells is presented. The system is designed to enable the manufacturing of small numbers of cells or components with industrial precision by using reconfigurable and adaptable production environments, so-called microenvironments. These can be individually climate controlled, so that required dewpoints of -50°C can be achieved for the different production steps. As a result, a highly modular and flexible system has been developed, both with regards to the cell chemistry to be produced and the geometric dimensions of the cells to be manufactured. The microenvironments presented in this approach allow for a faster and more energy efficient dehumidification of the required production space compared to conventional dry-room setups. Effects of different setpoints and human interaction on the energy consumption of the system, as well as the time necessary for climatic changes will be evaluated within this article.

Keywords: Battery Production; Flexible Manufacturing; Process Automation; Production Ramp-Up

1. Motivation

The demand for battery cell manufacturing capabilities is on the rise, particularly fueled by the increasing adoption of electromobility and other efforts towards electrification and a carbon neutral economy. This surge in demand is accompanied by rapid advancements and changes in cell chemistries on the one hand and manufacturing technologies on the other. Since conventional large-scale manufacturing lines are predominantly characterized by a rigidly linked setup, the future adaptability to new processes or material requirements is limited. This challenge is further increased by the substantial financial investment required for establishing battery cell manufacturing lines [1, 2].

Due to the limited flexibility in conventional setups, the current manufacturing landscape predominantly yields

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standardized battery cells, which while providing a good fit for many applications, do not serve the requirements of tailored solutions for smaller sectors such as aviation and maritime industries [3]. Moreover, the production of prototypes cannot be performed on industrial style equipment. It currently relies heavily on a manual assembly process, resulting in challenges related to the repeatability and accuracy of the finished product.

Another challenge within the battery cell manufacturing industry is the substantial energy consumption during production, particularly in maintaining the required dehumidified atmosphere within dry-rooms. These can amount up to 25% of the total energy demand during production, depending on the required dewpoints and internal moisture loads [4, 5]. Especially since future cell chemistries might have even more stringent dewpoint specifications than to date, this is a key concern for manufacturers [6].

2. Objective

In light of the aforementioned challenges, this paper proposes the implementation of an agile manufacturing system for the flexible and adaptable battery cell production. Large scale dry-rooms, as they are currently used in all European gigafactories are to be replaced by so-called microenvironments. Current setups are built to climatize and dehumidify entire production halls, mostly covering the process line from calandering all the way to the final sealing of the battery. In theory this provides the highest degree of flexibility, as production equipment can be re-arranged within the dry-room as needed. However, this advantage is often limited by the installed machinery, since rearrangements of the later are very costly and labor intensive. These commonly used central dry-rooms are equipped with airlocks for both material transport as well as the entrance of human operators into the manufacturing space [7, 8].

Not only the size itself contributes to the high energy demand of large dry-rooms. Other main sources are the exhaust air, which needs to be replaced by fresh air in order to provide sufficient oxygen to the operators, the leakage of the room as well as the operators themselves, who represent a constant source of moisture by perspiration for example. Additionally, the entire dry-room has to be dehumidified to meet the demands of the most moisture sensitive process step. This does not entail any negative impacts upon the product quality, but is far from optimal from an energetic point of view and leads to much higher operating expenditures (OPEX) [9]. This is especially true, since current setups often require a dewpoint of -20°C to -50°C. This value is not to be mistaken for the air temperature (usually approx. 21°C), as it represents the temperature, at which condensation would start to occur. It is equivalent to a relative humidity of less than 1% and a moisture content of fewer than 100 water molecules per million by volume [6]. It is noteworthy, that working in such a dry environment is not very convenient for the operators, which therefore have to leave the dry area regularly.

In order to achieve the largest possible reduction in terms of energy consumption, while also enabling a flexible system, a highly automated system is to be implemented [3, 10]. Human interaction with the process should be reduced to a minimum in order to enable a highly repeatable and reliable operation. This automation should be future proof by allowing for the individual adaption of different processes, without influencing the remainder of the production steps. A possible example could be the change from a wet to a dry coating operation, without influencing any downstream operations, such as stacking for example.

In previous works, the authors have proposed a modular set-up consisting of so-called microenvironments [11]. These represent individual dry-rooms, which are much smaller compared to conventional setups as found in industry to date and can be seen in Fig. 1. It hereby becomes possible to not only reduce the volume of air undergoing dehumidification, but also allows for the adjustment of individual dewpoints for different production steps, thus providing the potential for substantial energy savings.

The concepts for the automated material transport system between the different microenvironments as well as an example for individual process modules have been introduced in [12] and [13].

3. Approach

Four microenvironments were installed at the wbk – Institute of Production Science, in order to cover the process steps from coating the electrodes all the way to the final battery cell assembly. They have an interior floor space of 2,8m by 2,8m and are equipped with a central material handling robot, so that no human operator is required to be within the microenvironment during running production processes. In combination with necessary safety measures and advanced filter technologies it therefore becomes possible, to circulate part of the dry air back into the microenvironment, thus significantly reducing the waste air and therefore the energy consumption. Due to the lower overall volume and the rigidity of the construction, the air leakage to the outside of the dry room could also be reduced.

Fig. 1. One of the microenvironments, now installed at the wbk - Institute of production science.
Photographer: Martin Kleinert, pixl-Agentur, Hüfingen

Since the microenvironments are each equipped with their own dehumidifying unit, dewpoints can be individually adjusted for the steps along the process chain.

In order to allow for the flexible reconfiguration of the production setup, the roof and dehumidifying unit of a microenvironments can be detached from the rest of the microenvironment by the utilization of a crane. It hereby becomes possible to rearrange or change the process modules inside the cabins, allowing for optimal flexibility. The production modules themselves are equipped with zero-point-clamping systems which allow for a fast and easy reconfiguration. Manual teaching operations of the material handling robots are hereby minimized. In addition, the production modules are each equipped with a uniform interface, which connects to the central automation control for each microenvironment. The only hardware changes necessary when replacing a production module are therefore the connection of an ethernet line, as well as a power cable. Furthermore, compressed air is distributed to the individual production modules, if required for the production step. The finished production system can be seen in Fig. 2.

4. Experimental

The microenvironments are manufactured by *Exyte Technology GmbH* and are equipped with desiccant wheel-based dehumidifying. The dewpoint can be measured by two capacitive dewpoint sensors in both the airstream entering the microenvironment (inlet), as well as when being circulated back into the dehumidifying unit (outlet). Their calibration and accuracy of measurement has been confirmed by the use of an *S8000 Integrale* dewpoint mirror by *Michell Instruments Ltd*. In order to track the power consumption of the system, circuit breakers *NZMN2-PX100* by *Eaton Electric GmbH* with integrated energy measurement class 1 are installed within the central switching cabinet of each microenvironment. They allow for the separate current, voltage and combined power tracking for three phases each. The measured values for the dewpoints, power consumption and other process relevant parameters are drawn and archived from the central plc every 200ms using the software *ibaPDA Client* by the company *iba AG*.

Fig. 2. The four microenvironments with their corresponding dehumidifying units placed atop.
Photographer: Martin Kleinert, pixl-Agentur, Hüfingen.

In order to determine the energy consumption of the microenvironments, the target dewpoint for the outlet of the microenvironment is set to -50°C and the resulting power consumption is being observed. The setpoints for the overpressure of the room, compared to the ambient atmosphere (50Pa), room temperature (20°C), volume flow rate across the desiccant wheel (1.200 m³/h) and the air cooler (11°C) are not changed during the course of the experiments. The power consumption is being analyzed both after the initial startup of the system, as well as after several hours. Since the power consumption fluctuates heavily due to the periodic nature of heating elements for example, a moving average over the measured values for 5 minutes is being visualized.

The responsiveness of the system was tested by opening the access door to the microenvironments and observing the dewpoint measurements within the system. Such a scenario may become necessary when operators do have to perform manual maintenance operations, or when adjustments to the process have become necessary. The influence of both the duration of the opening, as well as the opening angle of the door was evaluated. The later one can be distinguished between a shallow opening angle of approx. 15°, which allows for sufficient air flow, so that a human operator does not suffocate within the microenvironment and a fully opened door (wide opening angle). The door was opened and closed manually according to a set timer. The actual duration of the opening could later be analyzed using the integrated safety solenoid interlock of the door. The exact point in time at which the door was closed was also used to align the different dewpoint time curves for a more accurate comparison. An overview of the different setups used for the evaluation can be found in Table 1. The experiments were performed in a sequential order, as listed below. The outside air temperature at the day of the experiments was around 15°C. A further point of differentiation within the experimental setups is the presence of an operator within the microenvironment. This was done to show the influence of a human upon the carefully controlled dry-room environment.

Table 1. Individual experimental setups.

Experiment	Door opened (planned) [min]	Door opened (actual) [mm:ss]	Opening angle	Operator present
1	5	05:07	Shallow	No
2	5	05:44	Shallow	No
3	5	05:01	Shallow	Yes
4	5	05:13	Shallow	Yes
5	5	05:19	Wide	No
6	5	05:08	Wide	No
7	10	10:10	Shallow	No
8	10	10:16	Shallow	No
9	15	15:11	Shallow	No
10	15	15:14	Shallow	No

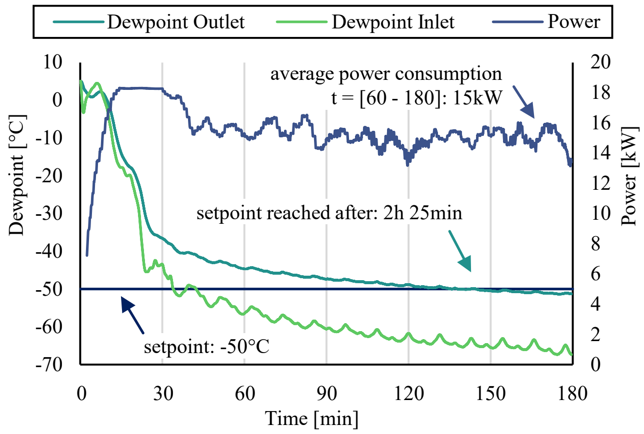

Fig. 3. The responsiveness of the microenvironment is shown. The setpoint of -50°C is reached in less than 2,5 hours.

5. Results

After the initial start of the system, it took the dehumidifying unit 2h and 25 minutes to reach the required dewpoint of -50°C within the microenvironment, as can be seen in Fig. 3. In order to reach the required setpoint, the unit blew fresh air with a dewpoint of down to -80°C into the microenvironment. After an initial peak, the power consumption averaged at 15kW after startup. This value further reduced itself throughout the operation of the microenvironment. For the 10th hour of operation after the startup, the average power consumption was 6,34kW with identical setpoints, as during the startup phase.

The presence of a human operator inside the microenvironment as well as the opening angle of the door both showed a significant impact upon the climate within the microenvironment. When opening the door to a shallow angle (experiments no. 1 and 2), the dewpoint quickly rises and settles at an equilibrium of approximately -40°C. After closing the door, the system takes around five minutes to readjust back to its original state of -50°C dewpoint temperature, as can be seen in Fig. 4. The additional effect of an operator within the dry-room (experiments no. 3 and 4) raises the dewpoint equilibrium to -30°C, while the duration to readjust to the original state only slightly increases.

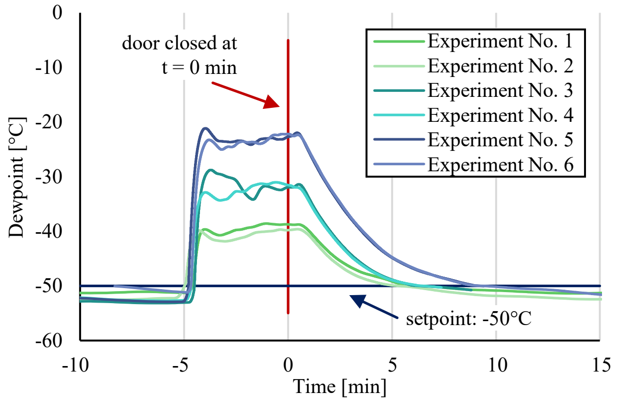

Fig. 4. The presence of operators within the dry-room (experiment 3 and 4) increases the dewpoint temperature significantly. So does fully opening the door to the microenvironment (experiment 5 and 6).

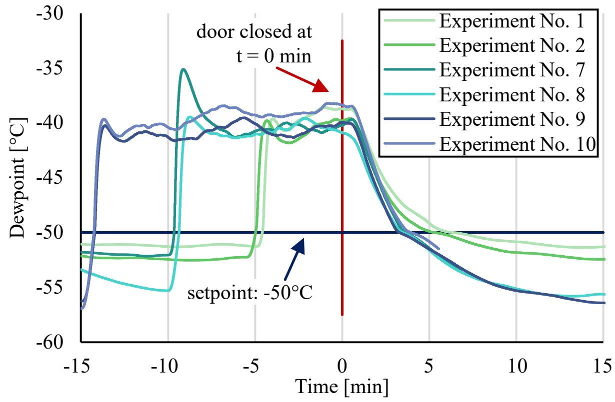

Fig. 5. Changing the duration for which the door of the microenvironment is opened barely has an influence upon the resulting dewpoint or the recovery time after closing the door.

The largest increase in humidity can be observed when fully opening the door of the microenvironment (experiments 5 and 6). The resulting dewpoint reaches approximately -20°C, even though the volume of fresh air introduced into the microenvironment is quickly quadrupled, compared to the values present before opening the door (400 m^3/h compared to 86m^3/h)

It can be seen in Fig. 5, that the time for which the door is opened barely influences the dewpoint which establishes within the microenvironment. An equilibrium of -40°C is reached, independent of whether the door has remained opened for 5, 10 or 15 minutes. Regarding the duration, necessary to regain the dewpoint of -50°C within the microenvironment, it can be observed, that the later experiments yield a shorter recovery time of well below five minutes.

6. Discussion

Detailed information about the electric power consumption of dry-rooms is only scarcely available in literature and if so, varies widely. For better comparison, values are normalized to the volume of the dry-room. Schünemann reports a normalized power consumption of 1,7 kW/m^3 for an industrial dry-room in 2015 [14]. Newer studies, such as Vogt et al. measure 0,17 kW/m^3 as a normalized value in 2021 [8]. The microenvironments presented in this paper require a normalized energy consumption of 0.32 kW/m^3, slightly doubling the value of Vogt et al.. However, it should be noted that Vogt et al. report an average measurement for a one month long continuous operation. Comparison to the short-term day-time measurements in this paper are therefore difficult to make, especially due to the influence of ambient air temperatures upon the energy consumption of a dry-room, which is significantly lower at night. It is expected, that the microenvironments presented in this paper show a similar, if not lower energy consumption, when measured in such a way.

The demonstrated responsiveness of the microenvironments far exceeds that of standard industrial setups today. Even though data is scare as well for this topic, expert discussions often times reveal start-up times of several days until a dry-room has reached its proper setpoint for operation. This is one of the reasons, why they are operated 24/7 in most factories, even if production is only happening in 2 shifts for example, thus further adding to the energy consumption. A startup time of less than 2,5 hours therefore represents a significant improvement compared to current industrial standards. It is especially relevant for smaller scale operations, as they can be found in research environments, for the manufacturing of prototypes or in other smaller scale operations.

Given the high degree of automation within the microenvironments, the omission of an airlock for the entrance of a human operator has been proven a valuable benefit for the cost effectiveness of the microenvironment. Even if a manual process intervention needs to take place, the recovery time of around five minutes for the microenvironment to reach its desired dewpoint setpoint is more than acceptable. This is especially true, since it could be observed, that the recovery time noticeably reduces with the operating time of the system and does not depend upon the length of the interruption. The reduction of the recovery time can be attributed to the same effect as the continuing decrease in overall energy consumption with the length of operation. Due to the thermal mass and inertia of the system, the startup phase requires a much larger energy input, compared to a system which has already reached a stable point of operation and only requires minor control impulses for the upkeep of required setpoints.

7. Conclusion and Outlook

This paper demonstrated the successful implementation of an agile manufacturing system based upon individual microenvironments. It allows for the fast adaption of the system to new requirements, as they might arise due to new cell chemistries, new manufacturing technologies or new requirements from specialized areas of industry. Several experiments were performed in order to assess the energy consumption, as well as the responsiveness of the system. Possible scenarios for necessary operator interaction with the automated system were evaluated as well. It could be proven, that the implemented microenvironments represent a highly responsive system. They can be used to easily adapt to new climatic requirements, while significantly reducing the amount of climatized air needed for the production. This results in substantial energy savings, especially since the power consumption normalized to the volume of the dry-room is comparable to that of large-scale industrial setups.

In addition to this proof of concept, future analysis could include long term operation of the microenvironments in order to retrieve more reliable data on the power consumption and responsiveness. The influence of different setpoints with regards to the required dewpoint for example could be evaluated as well. This way the potential benefits of microenvironments by operating different production steps at their respectively required climatic requirement could be further understood.

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