Parametric Energy Consumption Modeling for Cathode Coating Manufacturing of Lithium-Ion Batteries

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Abstract. In the process of manufacturing the positive electrode coating for lithium batteries, the slow and energy-consuming drying process greatly restricts the shortening of the production cycle and the improvement of energy efficiency of power lithium batteries. The purpose of this paper is to calculate the evaporation rate of N-methylpyrrolidone (NMP) solvent under different drying parameters in the first stage of evaporation and to predict the main energy consumption changes in the drying process in this stage. This research shows that, in the first evaporation stage of lithium battery coating manufacturing, when the inlet wind speed changes at 2~12 m s⁻¹, the evaporation rate of NMP solvent obtained in the coating will change in 1.18 × 10⁻³ ~ 2.88 × 10⁻³ g min⁻¹ cm⁻². For every 1 m s⁻¹ increase in wind speed, the energy consumption of electric heating increases by 57.60 kW on average.

1. Introduction
In recent years, the development of the electric vehicle industry has greatly promoted the development of power lithium battery [1-3]. However, there are many problems behind the explosive growth of power lithium battery industry, especially the high environmental impact of battery production. Among them, the drying process is the main time consuming and energy consuming link of positive electrode coating [2-4]. Compared with graphite negative electrode as a solvent [5, 6], the boiling point of positive electrode N-methylpyrrolidone (NMP) solvent is as high as 204 °C, and its drying temperature is mostly in the range of 90-150°C [7, 8]. The evaporation rate is relatively slow, leading to a long evaporation time and production cost. In addition, NMP is an explosive gas, and the volume ratio of the lower explosive limit in the air is 1.1% [9]. Therefore, evaporation requires large air volume to dilute the concentration of NMP in the air, which will cause high energy consumption [10].

Currently, Ahmed et al [9] measured the energy consumption of each process in the evaporation and recovery of NMP. Their results showed that producing a 10kWh battery pack required 420 kWh of electricity to evaporate the NMP solvent. The actual heating capacity of the drying process is 45 times that of NMP evaporation. Therefore, the setting of inlet air temperature and air volume of coating drying has a great influence on the energy consumption of drying. Deng et al [2] used Primary Energy Demand as the indicator to analyze the "Cradle to Gate (CtG)" stage of the current lithium battery pack. The results show that the primary energy consumption in the CtG phase is about twice that of the battery material. The drying process of coating manufacturing is the main energy source of the single battery
manufacturing process, accounting for 40% of the total energy consumption of the single battery manufacturing.

According to previous studies from Jaiser et al [11], the drying process of the electrode experiences a prolonged constant evaporation rate stage (first stage), next to a very short decreased rate stage. The reason from Jaiser et al is that capillary force within the porous structure drives the NMP solvent to the surface of the electrode, and thus, maintaining the evaporate rate of NMP. The dominant first stage evaporation also facilitates our calculation for the evaporation rate. Therefore, In this study, we will quantitatively calculate the evaporation rate in the first stage of evaporation under different drying parameters. Moreover, a parameterized process energy consumption model was established for the coated desiccants to calculate the change of main energy consumption in the drying system when the inlet wind speed was changed in the first stage of evaporation.

2. Method

2.1. The evaporation rate formula of the first stage of NMP solvent evaporation

According to the research of the same research group Su et al, we can get the evaporation rate formula of the first stage of the evaporation of NMP solvent [12].

First of all, we can use the type and the coating temperature ($T_s$):

$$q = h(T_m - T_s)$$

(1)

Where q is the heat flow density and h is the convective heat transfer coefficient.

Then we can also calculate the mainstream flow velocity of the coating surface ($V_{in}$) through the following equation:

$$V_{in} = v_{in} \cdot k$$

(2)

Where $V_{in}$ is the inlet wind speed of the drying box, k is the distribution wind coefficient, which is related to the vertical height (H) of the coating from the tuyere, the hydraulic radius (r) of the inlet and the space volume (V).

The evaporation rates of NMP can be calculated according to formula (3).

$$e_1 = \frac{c_{sa}(T_s) - c_{v}}{\gamma_{BL}}$$

(3)

Where $e_1$ is the evaporation rate at the first stage, the unit is (mol m$^{-2}$ s$^{-1}$).

Finally, it can be concluded that the relation between $T_s$ and $V_{in}$ of $e_1$ in evaporation stage 1 is the formula (4):

$$e_1 = 5.9931 \times 10^{-6} \cdot V_{in}^{0.12} (2.67159 \times 10^{-7} \cdot T_s^5 - 3.7468 \times 10^{-4} \cdot T_s^4 + 0.1989 \cdot T_s^3$$

$$-47.29151 \cdot T_s^2 + 4243.28404 \cdot T_s)$$

(4)

2.2. Energy consumption modeling of the drying system

In the dynamic drying system of lithium battery polar plate, the energy distribution includes: (1) temperature rise of pole plate substrate and coating solute; (2) temperature rise, vaporization and overheating of coating solvent; (3) electric heating energy consumption of dry medium (hot air); (4) energy consumption by the system for wind (fan); (5) energy consumption of wheel dehumidifier; (6) heat loss of drying equipment (negligible when small); (7) exhaust (waste air) sensible heat.

As shown in figure 1, the variable power of lithium battery positive plate desiccant comes from three parts: electric heater, fan and wheel dehumidifier. When the system begins to work, the fresh air is dried by the wheel dehumidifier. The dry air enters the heat exchanger and the return air of the drying box carries on the preliminary heat exchange in different pipelines. Then the dry air after preheating is sent to the heater for heating. After heating, it is sent to a drying oven to dry the wet pole. The return air after drying is returned to the heat exchanger and discharged as waste gas after heat exchange.
The drying system in Figure 1 is a stable thermodynamic open system, and the energy entering the system and the energy leaving the system have the energy conservation relationship in steady-state. For the first stage of evaporation studied in this paper, we assume that a static wet electrode is dried in a drying box, and the heat balance equation is established as follows:

$$\sum P_{elec} + \sum P_{fan} + \sum P_{WD} + \dot{Q}_{fresh} = \dot{Q}_{WA} + \dot{Q}_{EA} + \dot{E}_{EA} + \dot{E}_{WA} + \sum P$$

(5)

Where: $\sum P_{elec}$, total electrical heating power, kW; $\sum P_{fan}$, total fan power, kW; $\sum P_{WD}$, total power of wheel dehumidifier, kW; $\sum P$, heat loss of drying box, wheel dehumidifier, heat exchanger and pipe; $\dot{Q}_{fresh}$, enthalpy of fresh air, kW; $\dot{Q}_{WA}$, enthalpy of wet air, kW; $\dot{Q}_{EA}$, enthalpy of exhaust air, kW; $\dot{E}_{EA}$, the kinetic energy of exhaust air, kW; $\dot{E}_{WA}$, the kinetic energy of wet air, kW.

Main parameters in the heat balance equation are calculated according to the following formula:

$$\dot{Q}_{fresh} = q_{m} [1.005 T_{0} + d (2501 + 1.86 T_{0})]$$  

(6)

$$\dot{Q}_{WA} = q_{m} [1.005 T_{1} + d (2501 + 1.86 T_{1})]$$  

(7)

$$\dot{Q}_{EA} = q_{m} [1.005 T_{4} + d_{s} (r_{N} + C_{N} T_{4})]$$  

(8)

Where: 1.005, average constant pressure specific heat capacity of dry air, kJ kg$^{-1}$ °C$^{-1}$; 2501, latent heat of water gasification, kJ kg$^{-1}$ °C$^{-1}$; $q_{m}$, mass flow of air kg s$^{-1}$; $T_{0}$, initial air temperature, °C; $T_{1}$ is the temperature of wet air, °C; $T_{4}$, the temperature of exhaust air, °C; $d$, moisture content of air, kg (water vapor) kg (dry air)$^{-1}$; $d_{s}$, NMP content of air, kg(NMP) kg(dry air)$^{-1}$; $r_{N}$, latent heat of vaporization of NMP, kJ kg$^{-1}$; $C_{N}$, average specific heat capacity of NMP at constant pressure, kJ kg$^{-1}$ °C$^{-1}$.

Because evaporation is an endothermic process. Heat is supplied either by convection, conduction, radiation, or a combination of methods. The solvent evaporates from the coating surface, while the latent heat absorbed by evaporation cools the coating surface. Therefore, heat and mass transfer are carried out at the coated surface.
Assume that heating is provided by convection of hot air only and that the substrate is impenetrable. If the internal resistance of the solvent to the coated surface is ignored, then the heat and mass balance when lumped parameter system. According to the solvent manual, the evaporation energy consumption formula can be obtained [13]:

\[ Q = Lb\left[h(T_m - T) - e_r M_N r_N\right] \quad (9) \]

Where: \( L \), length of wet electrode, m; \( b \), width of the wet electrode, m; \( H \), heat transfer coefficient; \( M_N \), the molar mass of NMP.

The general heat transfer coefficient can be written as follows:

\[ h = K_{\infty}n \quad (10) \]

Where, \( K \), constant, are related to the physical properties of air and the collection size of the drying oven; \( n \), 0.6~0.8 (related to nozzle shape).

The return air temperature \( T_2 \) can be obtained by formula (11), (12) and (13):

\[ Q_{in} - Q_{RA} = \dot{Q} \quad (11) \]

\[ \dot{Q}_{in} = 1.005 q_m T_{in} \quad (12) \]

\[ Q_{RA} = q_m\left[1.005 T_2 + d_N (r_N + C_N T_2)\right] \quad (13) \]

Where: \( Q_{in} \), enthalpy of air at the inlet of the oven, kW; \( Q_{RA} \), Enthalpy of return air, kW; \( \dot{Q} \), the evaporation energy consumption, kW.

The above is the analysis and calculation model of energy balance and energy consumption of the drying system. On the whole, the analysis model shows the balance between the energy input, energy utilization and energy loss.

3. Results

On the basis of lithium battery positive electrode coating manufacturing, the base material is aluminum foil, the coating solute is NCM material, and the solvent is NMP solvent. The composition of adhesives and conductive agents are ignored, and the typical dry conditions are selected. The relevant known data are listed in table 1.

| Parameter                              | Data      |
|----------------------------------------|-----------|
| Width of wet electrode (b)             | 0.38 m    |
| Length of the wet electrode (L)        | 1 m       |
| Initial air temperature (T_0)          | 25 ℃      |
| Air temperature at the inlet of the drying oven (T_{in}) | 115 ℃ |
| Coating temperature (T_s)              | 70 ℃      |
| Inlet wind speed of drying oven (V_{in}) | 2 m s\(^{-1}\) |
| Moisture content of air (d)            | 0.015 kg kg\(^{-1}\) |
| NMP content of air (d_N)               | 0.017 kg kg\(^{-1}\) |
| Average specific heat capacity of NMP at constant pressure (C_N) | 6.44 kJ kg\(^{-1}\) °C\(^{-1}\) |
| Latent heat of vaporization of NMP (r_N) | 439.5 kJ kg\(^{-1}\) |
| The molar mass of NMP (M_N)            | 98.70 g mol\(^{-1}\) |
| Ventilation coefficient (k)            | 0.7       |
| n                                      | 0.6       |

According to the data in table 1, when the wind speed \( V_{in} \) is 2 m/s and the inlet wind temperature \( T_{in} \) is 115 ℃, the main drying results of the system are obtained as shown in table 2:
Table 2. Main drying results when $V_{in}=2$ m/s and $T_{in}=115^\circ$C

| Parameter                              | Data                        |
|----------------------------------------|-----------------------------|
| The first stage evaporation rate of NMP ($e_1$) | 0.00199 mol m$^{-2}$ s$^{-1}$ |
| Mass flow of air ($q_{ma}$)            | 1.72 kg s$^{-1}$            |
| Enthalpy of air at the inlet of the oven ($\dot{Q}_{in}$) | 198.79 kW                  |
| Enthalpy of return air ($\dot{Q}_{ra}$) | 73.27 kW                    |
| The evaporation energy consumption ($\dot{Q}$) | 125.52 kW                  |
| Electrical heating energy consumption ($\dot{Q}_{elec}$) | 149.94 kW                  |

The drying process of the system belongs to the energy exchange process between the electrode plate and air. The air enthalpy after heating is used for the latent heat of NMP solvent evaporation. In the energy consumption of the drying system in the first stage of evaporation, the heating air energy consumption is the main part of the energy consumption of the system, in which the electrical energy is converted into the enthalpy of the heated air without considering the impact of energy loss. In the first stage of evaporation, the evaporation of NMP consumes part of the energy, and the rest energy is discharged with the return air.

By changing the inlet wind speed, the evaporation rate and energy consumption of the system under different conditions are analyzed. On the basis of table 2, without changing the inlet air temperature $T_{in}$, the evaporation rate and energy consumption of $V_{in}$ at 2-12 m/s are calculated, and the results are shown in figure 2 and 3.

![Figure 2](image2.png)

Figure 2. Evaporation rate variation of $V_{in}$ at 2-12 m/s

![Figure 3](image3.png)

Figure 3. The energy consumption of $V_{in}$ at 2-12 m/s

According to the figure 2 and figure 3 show that the inlet $V_{in}$ during 2-12 m/s changes, the evaporation rate of $e_1$ increases, however, as the wind speed increase gradually, slowly in the increase of evaporation rate is reduced, the scope of its change in $1.99 \times 10^{-3}$ - $4.87 \times 10^{-3}$ mol m$^{-2}$ s$^{-1}$, or $1.18 \times 10^{-3}$ - $2.88 \times 10^{-3}$ g min$^{-1}$ cm$^{-2}$. With the improvement of inlet, the inlet air enthalpy and return air enthalpy value is also in constant rise. Evaporation energy consumption and electric heating energy consumption are also increasing. Although the energy consumption of electric heating is also increasing, the speed of improvement is also decreasing very slowly. For every 1m/s increase of inlet wind speed, the energy consumption of electric heating increases by 56.70 kW on average.

4. Conclusion

In this paper, the evaporation rate of the first stage of evaporation is calculated. According to the principle of energy conservation, the energy balance of the drying system of lithium battery was
established, and the calculation method of energy consumption was determined. By changing the inlet wind speed, the evaporation rate and energy consumption of the system under different inlet wind speeds are analyzed. When the inlet wind temperature is constant, the inlet wind speed is changed, and when $V_{in}$ changes from 2-12 m s$^{-1}$, the evaporation rate $e_1$ in the first stage of evaporation increases with the increase of the inlet wind speed, and its variation range is $1.18 \times 10^{-3} - 2.88 \times 10^{-3}$ g min$^{-1}$ cm$^{-2}$. At the same time, evaporation energy consumption and electric heating energy consumption are also constantly increasing. Whenever the inlet wind speed rises 1m/s, the energy consumption of electric heating increases by 56.70 kW on average.

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