

Article

Experimental Research on Heat Dissipation of Li-Ion Cells Under Various Conditions

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Abstract

Battery electric vehicles are a new technology used in underground mining, and as such introduce new thermal challenges due to confined space in working environments where heat accumulation can affect safety and ventilation requirements. This study, as a continuation of previous research, investigates heat dissipation from four Li-ion cells—three with NMC chemistry and one with LFP chemistry—under controlled charging and discharging rates (0.25C–1C) and ambient temperatures (30 °C and 40 °C). Eighty calculations were conducted to quantify heat flow and overall heat losses using natural convection and radiation models. The results show that heat emission strongly correlates with current rate, with the maximum heat flow being observed at 1C, particularly during discharging. Total heat losses ranged from 0.5013% to 1.74% of stored energy, with NMC cells exhibiting higher dissipation than the LFP one. Ambient temperature had minimal influence compared to the C-rate. These findings provide essential data for estimating heat load from battery electric vehicles in underground mining and ventilation planning.

Keywords: battery electric vehicles; lithium-ion cells; heat dissipation; heat losses; NMC; LFP

1. Introduction

With the advancement of technology in the mining industry in general, new opportunities have started to emerge, such as the usage of battery electric vehicles (BEVs), especially in underground mining. Among their many advantages, BEVs do not consume oxygen or emit harmful exhaust gases, which can affect ambient air quality, especially in underground conditions [1,2]. Another important factor is their low heat emission, along with their high efficiency and reduced noise levels, all of which greatly contribute to a more acceptable working environment [3]. Lithium-ion batteries have had and will have a huge impact on developing BEVs [4,5].

During charging and discharging processes, these batteries generate heat at varying rates, which increases the temperature of the surrounding air, which is already elevated in some cases due to the geothermal gradient (in general, the surrounding rock temperature is higher by 2.5–3.0 °C for each 100 m of increased depth).

Theoretical and experimental research has been reported in detail in recent years [6], identifying the main sources of heat in Li-ion cells as follows:

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- Joule or Ohmic heat, which is generated by the internal resistance of the cell opposing the flow of current [7–10];
- Electrochemical or reaction heat, which is associated with reduction–oxidation reactions and entropy changes during Li-ion intercalation and deintercalation. This is considered reversible heat and can be endothermic or exothermic depending on the process—charging or discharging [8,10,11];
- Polarization heat is generated by overpotentials and polarization effects during charge transfer, and it is also considered an irreversible heat source [8,12];
- Side-reaction heat is a heat source from side reactions such as electrolyte and membrane decomposition. However, these sources are typically negligible under normal operating conditions [13].

Battery-generated heat can be separated into reversible entropic heat and irreversible heat [14]. Reversible heat is primarily reaction heat caused by a change in entropy during electrochemical reactions. During charging, the process is endothermic, i.e., heat absorption, while during discharging, it is exothermic, i.e., heat release [15,16]. Irreversible heat comprises Joule heat, polarization heat, and side-reaction heat, and these forms of heat are always exothermic and contribute to the overall temperature rise in the cell [11,16].

Moreover, this heat can be treated as a form of energy loss, a perspective we also address in this paper. Appropriate thermal management is needed to ensure conditions for an optimal temperature range that supports high electrochemical performance and reduces degradation [14,17,18].

Battery charging and discharging lead to a temperature rise, mostly depending on the battery chemistry, rate of charging and discharging, etc. [19]. Heat dissipation from batteries causes a temperature elevation, and this depends on many factors, including the ambient temperature, battery chemistry, placement of a battery, distance between multiple cells inside the battery, etc. [20]. Multiple studies have been conducted from the 1970s for a variety of combinations, including the range of the Prandtl and Rayleigh numbers, as well as investigation of convection and radiation flow patterns, stability, aspect ratios and boundary conditions [21–23].

This paper uses previously published experimental results [24] as an input to calculate the heat flow of different cells under various operating conditions, in order to simulate the heat transfer in a real working environment. The outcome of this research will be the quantification of heat released from the cells, depending on their type, to ambient air, or in other words, to evaluate the heat dissipated during the charging and discharging processes. In the underground mining industry, this is called the heat load—the heat emitted into the working environment by a specific piece of equipment.

Diesel vehicles remain the most widely used form of transportation worldwide, and their energy efficiency and heat emissions have been extensively studied over the years. Since the specific energy of diesel fuel is known, the energy loss in terms of heat can be calculated, as McPhearson showed in [25]:

$$\dot{Q} = \frac{\dot{m}_f}{E} \cdot CV \quad (1)$$

where:

$\dot{Q}$ —heat flow (kJ/s)

$\dot{m}_f$ —fuel consumption per rated power (L/kW)

E —energy (kW·s)

CV —calorific value of fuel (kJ/L)

In contrast, battery electric vehicle (BEV) technology is relatively new, and such information is not yet publicly available. While approximate percentages are sometimes cited, they often lack reliable references, and the estimation of heat released from BEVs is

not as straightforward as for diesel machines (Equation (1)). There are several heat sources related to BEVs: stationary object—charging station with heat emission from charging device and battery; and mobile object—vehicle with heat emission from battery, inverters and electric motors.

Previous research on heat dissipation of Li-ion batteries is more focused on the impact of extreme temperatures and high currents on battery performance (low temperatures cause degradation of battery capacity, and high temperatures represent safety risk, as do high currents—C-rates).

In the mining industry, more precisely, in underground mining, battery-powered vehicles are relatively new technology—mostly developed since 2020. The focus of our research is on the operation of these machines in confined spaces, such as in underground mines, over longer periods (moderate to low C-rates, charging and discharging periods for 2–4 h) at temperatures ranging from 30 to 40 °C. In such conditions, every heat source is important and must be accounted for, to properly evaluate the working environment since this temperature range is critical for prolonged human labor and thermal regulation of the human body. There is little to no available research on this topic related to the mining industry.

Tripti et al., 2015 [26] showed that heat is an unavoidable part of mining activities and that it must be addressed by ventilation to remove it in order to improve working conditions for humans. This paper also provides fundamentals on heat generation by mining equipment, but battery electric vehicles were not included in a review. Wroblewski et al. [27] provided a review of methods for heat load establishment in underground mining, taking into consideration the most important sources of heat. Mining machines were identified as a highly relevant heat source, but only diesel and AC-powered equipment are analyzed. Battery electric vehicles are omitted. A more recent paper by Aitsev et al. [28] researched air temperature in the vicinity of various types of operating underground mining equipment. Their focus was on machines powered by internal combustion engines and AC electric motors, which they tested with thermal imaging methods. No BEV was tested in this research.

Jacobs et al. [29] focused on operational and health and safety issues, analyzing exposure to diesel particulate matter (DPM), sustainability and zero-emission. They have researched replacement options for diesel-powered load-haul-dump (LHD) machines with electric LHDs with trailing cable, i.e., AC-powered LHDs. Battery-powered LHDs were not included in their analysis, nor were heat emissions.

Kulsap et al. [30] provided a broad analysis on BEV applications in underground mining, with a focus on benefits, challenges and health and safety. It is shown that battery electric vehicles provide significant benefits and improve health and safety, and associated risks were also identified. Ventilation on demand is mentioned as an important benefit in terms of cost reduction (opportunity to manage main fan operation relative to mining conditions), but without details on heat emission from BEVs.

It can be concluded that there is a lack of research related to heat dissipation from battery electric vehicles operating in confined spaces, such as underground mines—where it is known as heat load. This is because the machines are operating in specific conditions, referring to a narrow temperature range of significance and low charging/discharging rates. The narrow temperature range is between 30 and 40 °C, while the low rates are between 0.5C and 0.25C. The mentioned temperature range is well within the operational values of Li-ion cells, but on the other hand, it is critical for human labor—temperature above 30 °C is considered as a high occupational risk for human labor due to heat stress of the human body, particularly in confined spaces. The issue of C-rates is relevant since existing batteries for underground mining BEVs are quite large (as an example, batteries for 50 t payload underground trucks have capacity of over 350 kWh), with promoted

autonomy of 2 to 4 h, corresponding to C-rates of 0.5C to 0.25C—higher C-rates are just not practical for such batteries (more frequent charging, machine idling and battery replacement/swapping).

Available research on Li-ion batteries is almost exclusively focused on battery performance at boundary temperatures, for evaluating their capabilities at subzero temperatures or the risk of thermal runaway at upper boundary temperatures (60 °C and over) [31]. Also, these studies are commonly performed with moderate to high C-rates, often with double-digit C-rates (a rate of 10C translates to complete battery discharge in 6 min).

The research presented in this paper is designed to estimate heat dissipation in realistic operational conditions of BEVs in confined space, where each heat source is relevant from the perspective of occupational health and safety. As noted above, there are no available data on this topic.

This paper refers to heat emissions from cells, which are calculated using measured temperature data reported in [24]. The results are presented in terms of absolute heat emission values, and the influence of operating conditions on heat release is analyzed. The underlying electrochemical mechanisms within batteries, that are causes of temperature changes, are beyond the scope of this paper.

2. Materials and Methods

2.1. Testing Method and Setup

The objective of the presented research is to calculate the amount of heat emitted by cells tested under varying ambient temperatures and different charging/discharging rates, based on previously published results [24]. This chapter provides a brief description of the cell testing methodology, while more details are available in [24].

The tests were systematically planned and conducted under the same conditions: all cells were placed in the same location within the thermal chamber, maintained at constant ambient temperatures, and all measurements were taken using the same equipment. Four lithium-ion 18650 cells were tested—three with NMC chemistry (P26A, VTC5A, and 25R) and one with LFP chemistry (Heter). Specifications of the tested cells are given in [24].

The tests were carried out in a Colo DRYSC 136 thermal chamber (convection oven, manufactured by Colo LabExperts, Polje ob Sotili, Slovenia). Cell and ambient temperatures were measured using type J and type K thermocouples, respectively. Temperature data were recorded using a Testo 175T3 data logger, with a precision of $\pm 0.5\text{ °C} \pm 1$ digit. The Siglent SPD 3303C and Siglent 1000X instruments (manufactured by Siglent.eu, Helmond, the Netherlands) were used for charging and discharging the cells, respectively. Both instruments have an accuracy of $\pm 0.5\% + 1$ digit for both voltage and current. Additionally, a Fluke V3001FC voltmeter (manufactured by Fluke, Eindhoven, the Netherlands) was used to precisely measure the voltage directly at the cell terminals, with an accuracy of $\pm 0.09\% + 3$ digits, thereby eliminating losses due to wiring.

The cells were charged to their nominal voltages (4.2 V for NMC cells and 3.65 V for the LFP cell), with a cut-off voltage of 2.7 V in the discharging tests. Charging and discharging were performed at constant current rates of 0.25C, 0.33C, 0.5C, 0.75C, and 1C, corresponding to test durations of 240, 180, 120, 80, and 60 min, respectively. In comparison to the study presented in [24], this research also includes tests conducted at a 0.25C rate.

Experiment setup is shown in Figure 1.

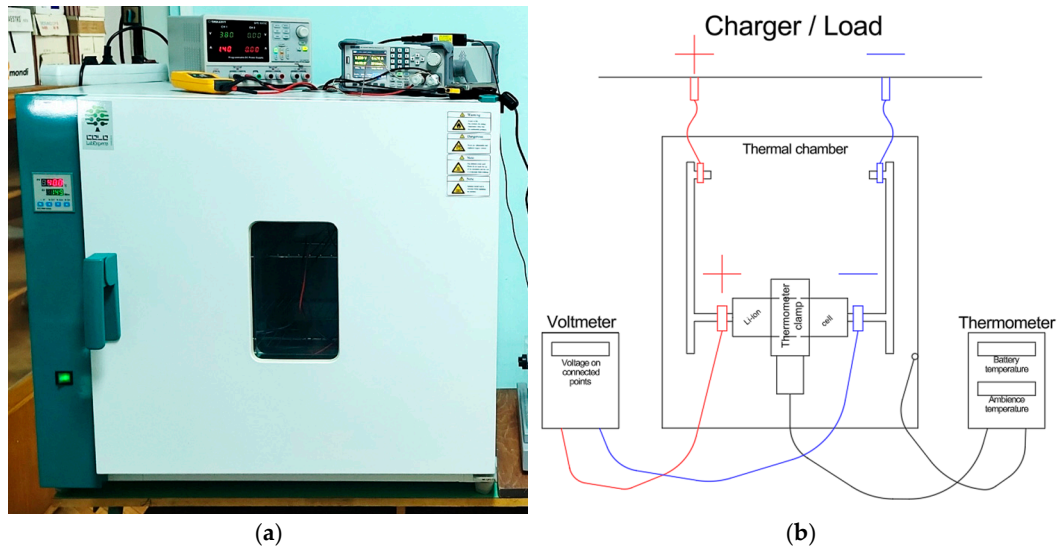


Figure 1. Experiment setup [24]. (a) Photo of the experiment; (b) Scheme of the setup.

All tests were conducted at constant ambient temperatures of 30 °C and 40 °C. Each of the four cells was tested during both charging and discharging processes, at two ambient temperatures and five different current rates, resulting in a total of 80 tests. Prior to testing, the cells were preheated to the target temperature to ensure that any observed temperature changes were solely due to internal electrochemical reactions during charging/discharging. All test results are provided in the Supplementary Materials.

The obtained results include measurements of the cell surface temperature and the ambient air temperature, recorded at 10 s intervals. These temperature data are presented and discussed in detail in [24].

Based on these results, the objective of the research was to determine the heat transfer to the ambient air and to evaluate the amount of heat dissipated during the charging and discharging processes.

2.2. Calculation of Heat Transferred to the Surroundings

Batteries represent complex systems with coupled electrochemical and thermal processes [29]. During the charging and discharging process, some portion of energy is transformed to heat within a battery, inducing an increase in thermal internal energy, heat transfer through the battery, and heat transfer to the surroundings (Equation (2)).

$$c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{q} \quad (2)$$

where:

ρ —represents average density of the battery

c —average heat capacity of the battery

λ —coefficient of heat conductivity of the battery

$\dot{q}$ —represents heat transfer to the surroundings from the surface of the battery by convection and by radiation (Equation (3)):

$$\dot{q} = \dot{q}_{conv} + \dot{q}_{rad} \quad (3)$$

Convective heat transfer from the battery surface is both from lateral and cover surfaces (Equation (4)).

$$\dot{q}_{conv} = \dot{q}_{lateral} + \dot{q}_{cover} \quad (4)$$

The equation used for calculating convective heat flow, along with the values for thermal conductivity, Prandtl number, and kinematic viscosity, are adopted from [32,33].

Since the scenario involves natural convection from a cylindrical body, the heat flow is calculated using the following equation:

$$\dot{Q}_{conv} = \Delta T \cdot \alpha_l \cdot S_l + \Delta T \cdot \alpha_c \cdot S_c \quad (5)$$

where:

ΔT —difference between the cell temperature and the ambient temperature [K]. Relevance for this research is based on the assumption that the cell temperature should always be equal to or higher than the ambient temperature [34]

α_l —coefficient of convective heat transfer from the lateral surface [$\frac{W}{m^2 \cdot K}$]

α_c —coefficient of convective heat transfer from the cover surface [$\frac{W}{m^2 \cdot K}$]

S_l —lateral cell surface area [m^2]

S_c —cover cell surface area [m^2]

The convective heat transfer coefficient is calculated as

$$\alpha = \frac{Nu \cdot \lambda}{D} \left[\frac{W}{m^2 \cdot K} \right] \quad (6)$$

where:

Nu —Nusselt number

λ —thermal conductivity for given temperature [$\frac{W}{m \cdot K}$]

D —cell diameter. $D = 2r$

Values for the Prandtl number, thermal conductivity, and kinematic viscosity are available at discrete temperatures of 20 °C, 30 °C, 40 °C, and 50 °C. Therefore, interpolation is used to estimate these properties at the required intermediate temperatures.

The Nusselt number for natural convection from a lateral surface (horizontally placed cylinder) is calculated as follows:

$$Nu = C' \cdot (Gr \cdot Pr)^{n'} \cdot \left(\frac{Pr_f}{Pr_A} \right)^{0.25} \quad (7)$$

where, for a horizontal cylinder, $10^3 < (Gr \cdot Pr)_f < 10^8$:

C' —constant that depends on geometry, orientation, type of flow, boundary conditions and choice of characteristic length. In this instance, $C' = 0.5$ [34];

Gr —Grashof number

Pr —Prandtl number

n' —constant that depends on type of flow (laminar or turbulent). In this instance, $n' = 0.25$ [20];

Pr_f —Prandtl number for fluid

Pr_A —Prandtl number for fluid, but for wall temperature (in this case, cell temperature)

For the cover surfaces, the Nusselt number is calculated by Equation (5), but in this case, $C' = 0.76$ [33]. The characteristic length is the diameter of the plate, D [35].

The Grashof number is a dimensionless number that quantifies the ratio of buoyant to viscous forces within a fluid boundary layer, thus indicating the onset and intensity of natural convection. The Prandtl number, also dimensionless, characterizes the relationship between a fluid's momentum diffusivity (viscosity) and thermal diffusivity (thermal conductivity), indicating the relative effectiveness of momentum and heat transport within the fluid.

The Grashof number is calculated using the following equation:

$$Gr = \frac{\beta \cdot g \cdot D^3 \cdot \Delta T}{\nu^2} \quad (8)$$

where:

β —coefficient of volume expansion ($\beta = 1/T_{cell}$)

g —gravitational acceleration ($g = 9.81 \text{ m/s}^2$)

ν —kinematic viscosity

Heat transferred by radiation is calculated from Equation (9) [33]:

$$\dot{Q}_{rad} = C_c \varepsilon S_{ef} \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \quad (9)$$

where:

C_c —constant of radiation

ε —emission coefficient

S_{ef} —effective surface of radiation

T_1 —temperature of the surface of the battery

T_2 —temperature of the chamber walls. In this case, it is assumed that the temperature of the wall is equal to the temperature of the surrounding air.

It is evident that most variables involved in the calculation of the convective heat transfer coefficient and overall heat flow are temperature-dependent. Once the heat flow is determined, the total heat transferred to the surroundings over the observed time interval can be calculated using the following expression:

$$Q = \sum_{i=1}^n Q_i \quad (10)$$

where:

Q_i —heat transferred from cell in i th interval of time

n —number of time intervals from experimental research

Each time interval equals 10 s.

$$Q_i = \frac{\dot{Q}_i + \dot{Q}_{i+1}}{2} \tau \quad (11)$$

This equation represents an average sum of heat flow at two successive measurement points. Since the measurements were taken every 10 s, $\tau = 10 \text{ s}$.

2.3. Overall Heat Losses

A Li-ion cell can be regarded as an energy storage device. When the cell is charged, it stores a certain amount of energy, which can be calculated using the following expression [36]:

$$E = C \cdot U \cdot 3600 \text{ [J]} \quad (12)$$

In this context, C (Ah) represents the cell's capacity, and U (V) represents the nominal voltage of the cell. It should be noted that the nominal voltage refers to the average voltage at which the cell typically operates. Although this value is specified by the manufacturer and is considered standard for a given cell type, it may differ slightly from the actual average voltage observed during operation. This discrepancy was examined, and it was found that the operational voltage is indeed slightly higher than the nominal value—by approximately 4%. However, this difference is minimal and does not significantly affect the outcomes of this research. Therefore, the nominal voltage is used for all subsequent calculations.

The overall heat emitted during one complete cycle (charging and discharging) includes the heat transferred to the surroundings via natural convection and radiation following both the charging and discharging phases. Additionally, there is a pause between these two phases during which the cell undergoes cooling; the heat dissipated during this cooling period is also accounted for. The initial heating of the cell is not considered in the calculation, as the cell is preheated to the target testing temperature prior to the start of

the test. Therefore, the overall heat emitted—or the heat transferred to the surrounding environment—during one cycle is given by

$$Q_{\text{overall}} = Q_{\text{charging}} + Q_{\text{cooling}} + Q_{\text{discharging}} + Q_{\text{cooling}} \quad (13)$$

$$Q_{\text{cooling}} = m \cdot c \cdot \Delta t \text{ [J]} \quad (14)$$

where:

m —cells mass [kg]

c —specific heat capacity of a cell [J/kg·K]; the accepted specific heat capacity value for the NMC cells is $c = 1000 \text{ J/kg·K}$, and for the LFP cell, $c = 1150 \text{ J/kg·K}$ [37,38]

Δt —difference between cell temperature at the end of a charge/discharge cycle and ambient temperature.

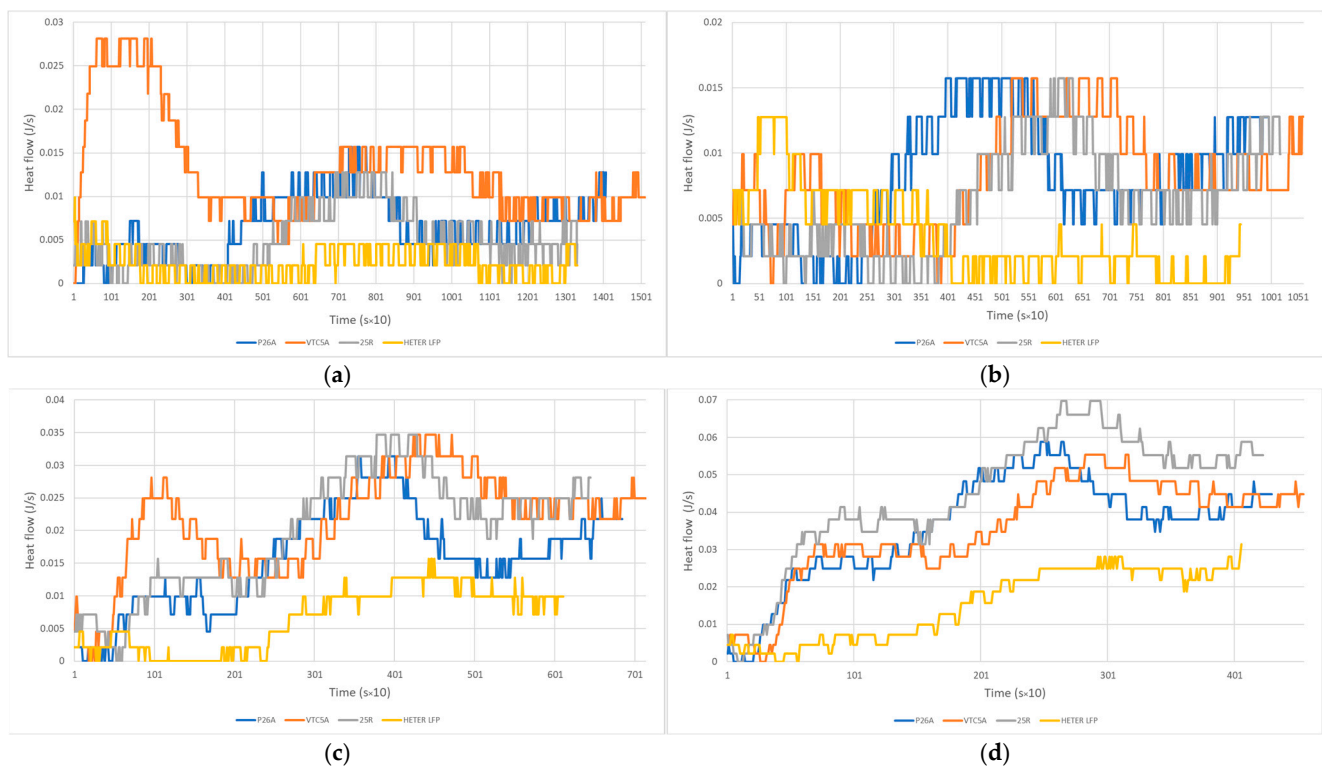
As previously mentioned, the overall heat emitted (Q_{overall}) represents the energy lost during a complete charging and discharging cycle in the form of heat (measured in joules). Consequently, the ratio of this value to the energy stored in the cell (as defined in Equation (12)) can be interpreted as energy loss due to heat dissipation. The following expression can be used to quantify these losses:

$$Q_t(\%) = \frac{Q_{\text{overall}}}{E} \cdot 100 \quad (15)$$

The equation above gives the cell's losses in one cycle, in percent.

3. Results and Discussion

Results for the calculated heat flow of the four tested cells, where three were based on NMC chemistry and one on LFP chemistry, are presented in Figure 2. Tests were performed at a temperature of 30 °C and with 0.25C, 0.33C, 0.5C, 0.75C, and 1C charging rates.



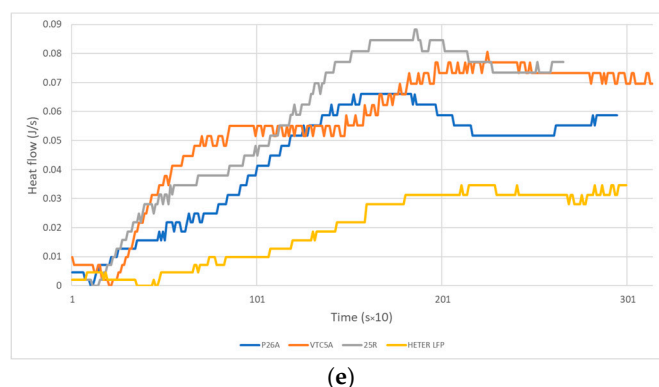


Figure 2. Heat flow of cells during charging at temperature of 30 °C with charging rates of (a) 0.25C, (b) 0.33C, (c) 0.5C, (d) 0.75C, and (e) 1C.

As shown in Figure 2, four datasets of heat flow are presented—one for each tested cell. The vertical axis represents heat flow in joules per second [J/s], while the horizontal axis represents time in units of 10 s [$s \times 10$]. The unit of heat flow is watt [W], which corresponds to joules per second [J/s]. The results are presented in [J/s] for more intuitive understanding of energy dissipated per unit of time, since the durations of the tests were not equal (the 1C test lasted 1 h, and the 0.25C test lasted 4 h). For a clearer picture, the heat flow axis in each graph is not in the same ratio as that used for the other heat flow axes in the other graphs.

It is evident that the lowest heat flow values occurred during charging at 0.25C and 0.33C. An exception is observed in the VTC5A cell while charging at 0.25C (Figure 2a, orange line), during which it exhibits a pronounced spike in heat flow at the beginning of the test. This spike did not recur in subsequent tests. This anomaly resulted in over 198 J of heat being emitted, whereas the other cells produced between 2.5 and 7 times less heat under the same conditions. This observation is further elaborated later in this chapter (see Table 1).

Table 1. Overall heat transferred to surroundings by the tested cells at 30 °C [J].

	30 °C									
	Charging					Discharging				
	0.25C	0.33C	0.5C	0.75C	1C	0.25C	0.33C	0.5C	0.75C	1C
P26A	90.45	81.30	107.64	154.70	128.81	76.12	68.15	56.84	69.37	115.84
VTC5A	198.96	86.04	154.03	162.83	175.94	76.23	69.48	63.83	65.64	120.28
25R	65.59	65.71	127.55	189.54	151.26	67.47	50.09	68.98	158.41	166.95
HETER	31.41	35.20	40.80	62.43	59.42	31.68	28.33	26.14	28.73	50.35

It is also evident that the rate of change in heat flow increases with higher charging rates. However, heat flow does not follow a consistent trend within any individual test. This irregularity is observed across all tests and is particularly pronounced at higher charging rates. Typically, an initial increase in heat flow is followed by a stagnation period and, in some cases, a subsequent decline. Notable examples include the VTC5A cell (Figure 2c, orange line) and the P26A cell (Figure 2e, blue line). This behavior is more visible in cells with NMC chemistry than in the LFP cell. For instance, the 25R cell (Figure 2d, gray line) exhibits two maximums, indicating two cycles of increase–stagnation–decrease in heat flow (Figure 2c,d). These variations are most likely due to different electrochemical reactions occurring within the cells at varying temperatures and charging rates.

It is important to note that higher heat emission is influenced not only by the duration of charging but also by the magnitude of the heat flow. At the beginning of the charging

process, the heat flow is low—often near zero—because it takes time for the internally generated heat to reach the cell surface and become detectable by the thermocouple. As the test progresses, the cells begin to exhibit the described heat generation behavior.

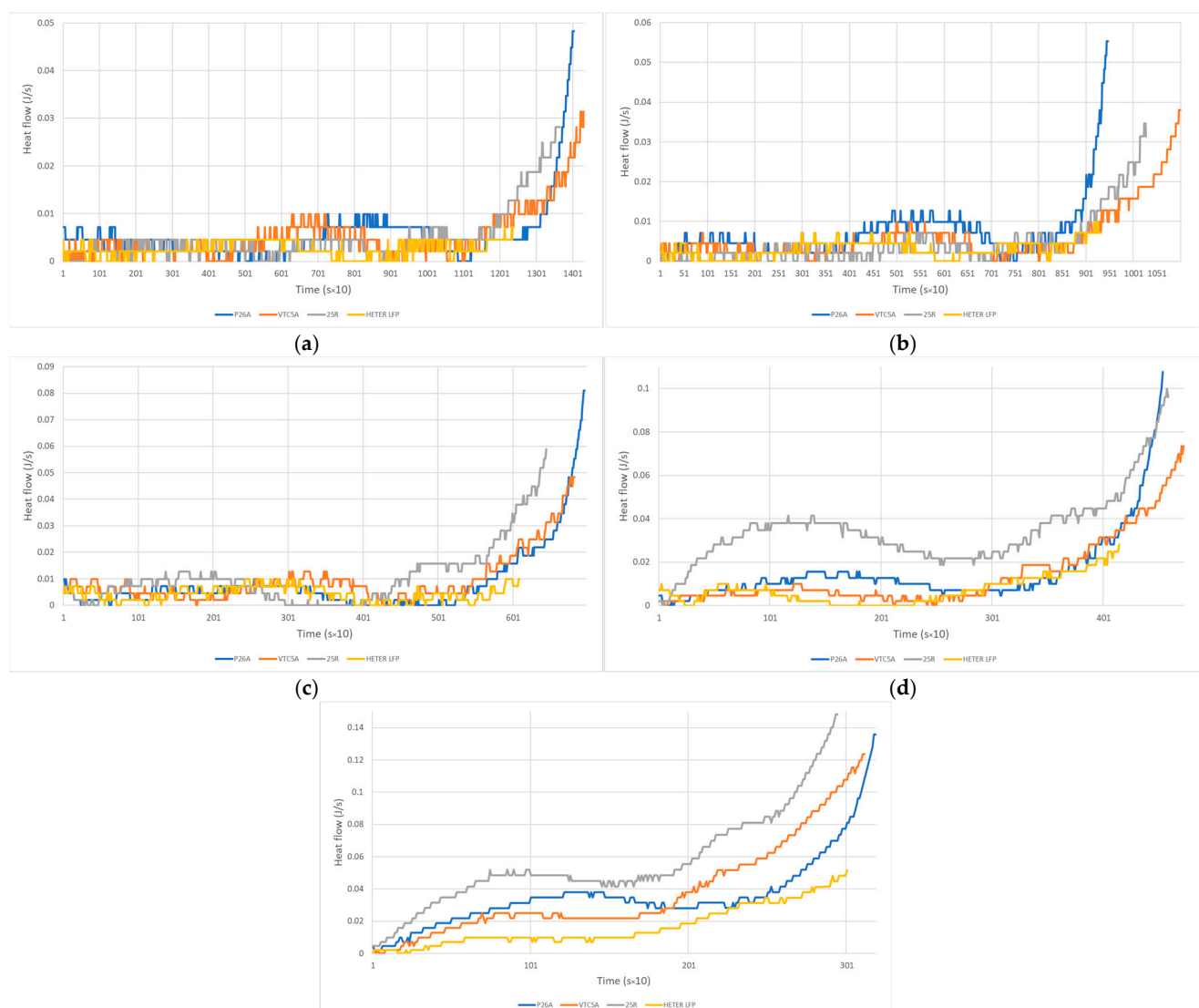
All NMC cells display similar behavior at lower charging rates (0.25C, 0.33C, and 0.5C), with more pronounced differences emerging at higher rates (0.75C and 1C). The highest heat flow was recorded for the 25R cell during charging at 1C (Figure 2e).

The HETER cell, which is based on LFP chemistry, consistently exhibited the lowest heat emission (yellow line) across all tests. This outcome is expected due to its different electrochemical composition [1]. Its heat flow curve is more linear to sublinear compared to the other cells. In Figure 2c–e, the HETER cell shows a slow initial increase in heat flow, maintaining a sublinear trend throughout the tests, with only slight variations in the rate of increase and periods of stagnation.

Conclusions of the charging test at 30 °C are as follows:

- Higher charging rates resulted from higher heat flow, hence the highest rate was at 1C.
- NMC cells exhibited irregular patterns of heat flow fluctuations (increase—stagnation—decrease cycles).
- The LFP cell demonstrated a steady, sublinear increase in heat flow.

Heat flow curves for all cells during discharge at temperature of 30 °C, with 0.25C, 0.33C, 0.5C, 0.75C and 1C discharging rates, are shown in Figure 3.



(e)

Figure 3. Heat flow of all cells during discharge at temperature of 30 °C, with discharging rates of (a) 0.25C, (b) 0.33C, (c) 0.5C, (d) 0.75C, and (e) 1C.

The heat flow graphs obtained during the discharging tests reveal distinct cell behaviors compared to the charging tests. For most of the test duration at discharging rates of 0.25C, 0.33C, 0.5C, and 0.75C, the heat flow remained very low. Only the discharging tests conducted at the highest rate (1C) showed a noticeable separation among the heat flow curves.

A characteristic feature observed in all discharging tests of NMC cells is a rapid increase in heat flow toward the end of the test—an effect not observed during charging. This additional heat generation is primarily attributed to increased internal resistance and reduced electrochemical efficiency at lower states of charge [19,20].

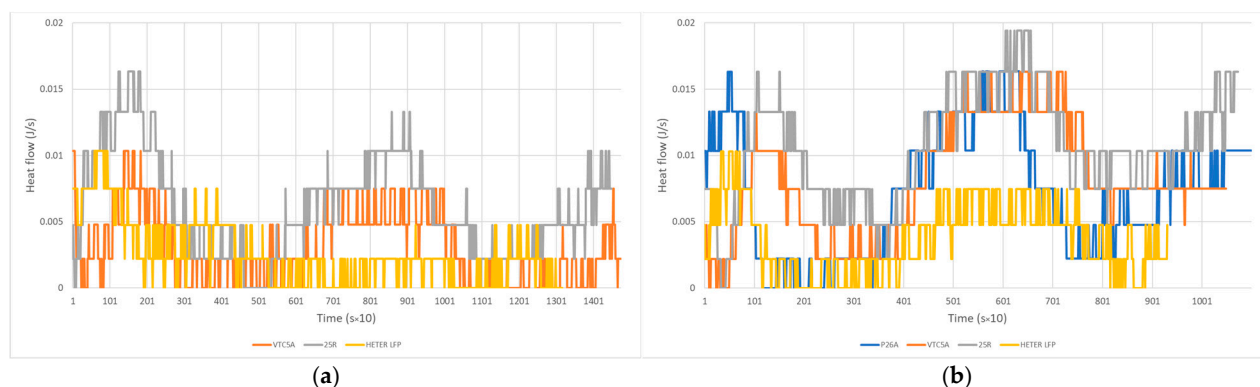
The highest heat flow during discharging was recorded for the NMC cell 25R at rates of 0.75C and 1C, as shown in Figure 3d,e. Notably, this same cell also exhibited the highest heat flow during charging at the corresponding rates. The actual calculated values of heat flow for all cells are presented later in this chapter.

The LFP cell (HETER) demonstrated the lowest heat flow during discharging, consistent with the results from the charging tests at the same temperature. The heat flow curve for this cell also followed a relatively linear trend during discharging, without the sharp rise observed in the NMC cells toward the end of the test.

To summarize the observations from the discharging tests at 30 °C:

- Heat flow was lower at lower discharge rates.
- NMC cells had the highest (maximum) heat flow in the 1C discharge test.
- The LFP cell demonstrated a linear increase in heat flow, without spiking at the end of the test.
- Heat flow rose sharply toward the end of the NMC cell tests, due to increased internal resistance and reduced electrochemical efficiency. In these experiments, most of the heat was emitted during the last 20% of test duration.

Heat flow curves for all cells during charging at temperature of 40 °C, with 0.25C, 0.33C, 0.5C, 0.75C and 1C charging rates, are shown in Figure 4.



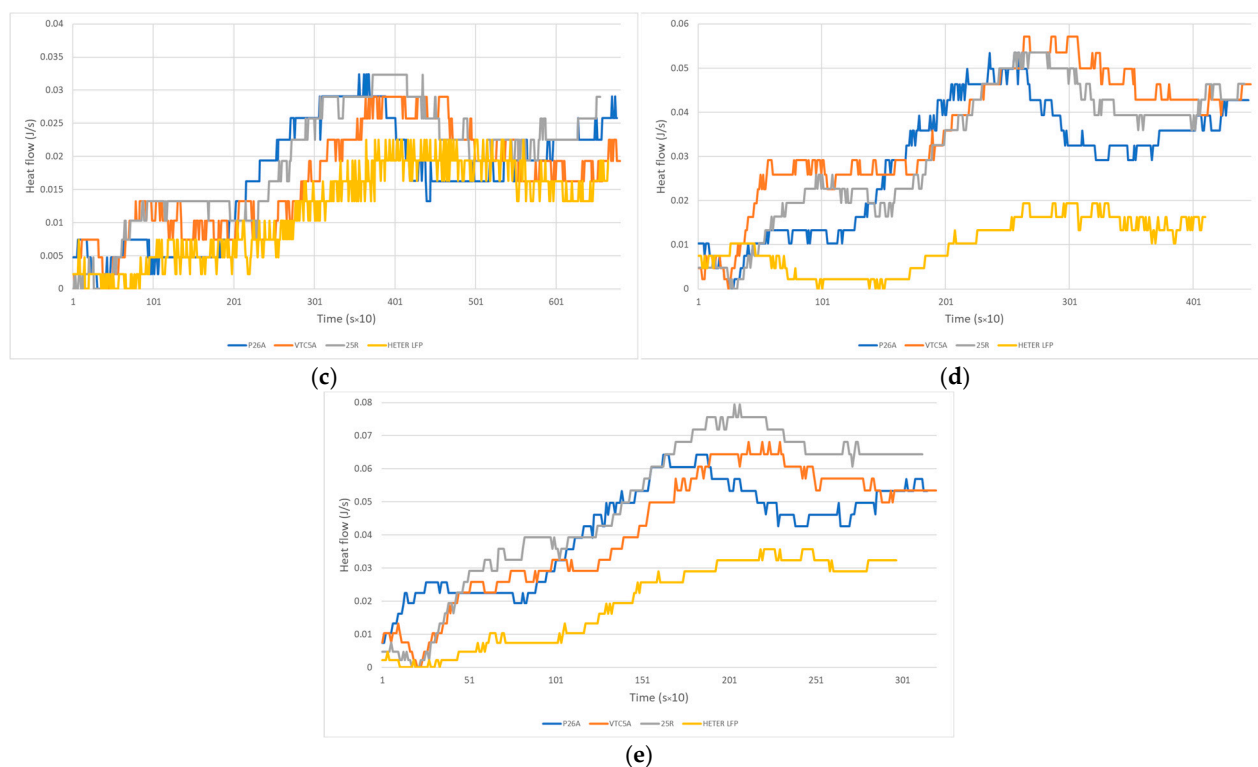


Figure 4. Heat flow of all cells during charging at temperature of 40 °C, with charging rates of (a) 0.25C, (b) 0.33C, (c) 0.5C, (d) 0.75C, and (e) 1C.

It can be observed that the tests conducted at an ambient temperature of 40 °C with charging rates of 0.25C and 0.33C produced heat flow curves that were horizontal or sub-horizontal, with minimal fluctuations. This indicates that the heat flow remained relatively constant throughout the duration of these tests. In contrast, tests performed at higher charging rates of 0.75C and 1C exhibited a much steeper increase in heat flow, particularly during the initial 10 min. The test conducted at a 0.5C charging rate displayed intermediate behavior, clearly indicating that heat flow varies more rapidly with increasing current.

The NMC cells during charging at 40 °C demonstrated behaviors similar to those when tested at 30 °C. Specifically, the heat flow typically increased, followed by a stagnation period and, in some cases, a subsequent decrease. In certain tests, this cycle repeated twice, as observed in the 25R cell at higher charging rates. The LFP cell (HETER) continued to exhibit the lowest heat flow, maintaining a linear to sub-linear trend across all tests.

Unlike the discharging tests, no significant spikes in heat flow were observed toward the end of the charging tests. Furthermore, all tests were completed within the expected durations for their respective charging rates: 240 min for 0.25C, 180 min for 0.33C, 120 min for 0.5C, 80 min for 0.75C, and 60 min for 1C—consistent with the tests conducted at 30 °C.

There appears to be no substantial difference in heat flow maximums between the charging tests conducted at 30 °C and those at 40 °C for the lower charging rates (0.25C, 0.33C, and 0.5C). However, some NMC cells, such as 25R and VTC5A, exhibited higher maximum heat flow values at 30 °C when charged at higher rates. Once again, the 25R cell recorded the highest heat flow at 1C (Figure 4e).

Outtakes of the charging tests at 40 °C are as follows:

- Observed trends were similar to those in tests at 30 °C, with flatter curves at lower rates and steeper and more separated curves at higher rates.

- Heat flow fluctuations were again present in tests of NMC cells, due to electrochemical reactions.
- The heat flow of the LFP cell was smoother, with minimal fluctuations.
- Overall, no major differences in maximum heat flow were observed, compared to the test performed at 30 °C.

Heat flow curves for all cells during discharge at temperature of 40 °C, with 0.25C, 0.33C, 0.5C, 0.75C and 1C discharging rates, are shown in Figure 5.

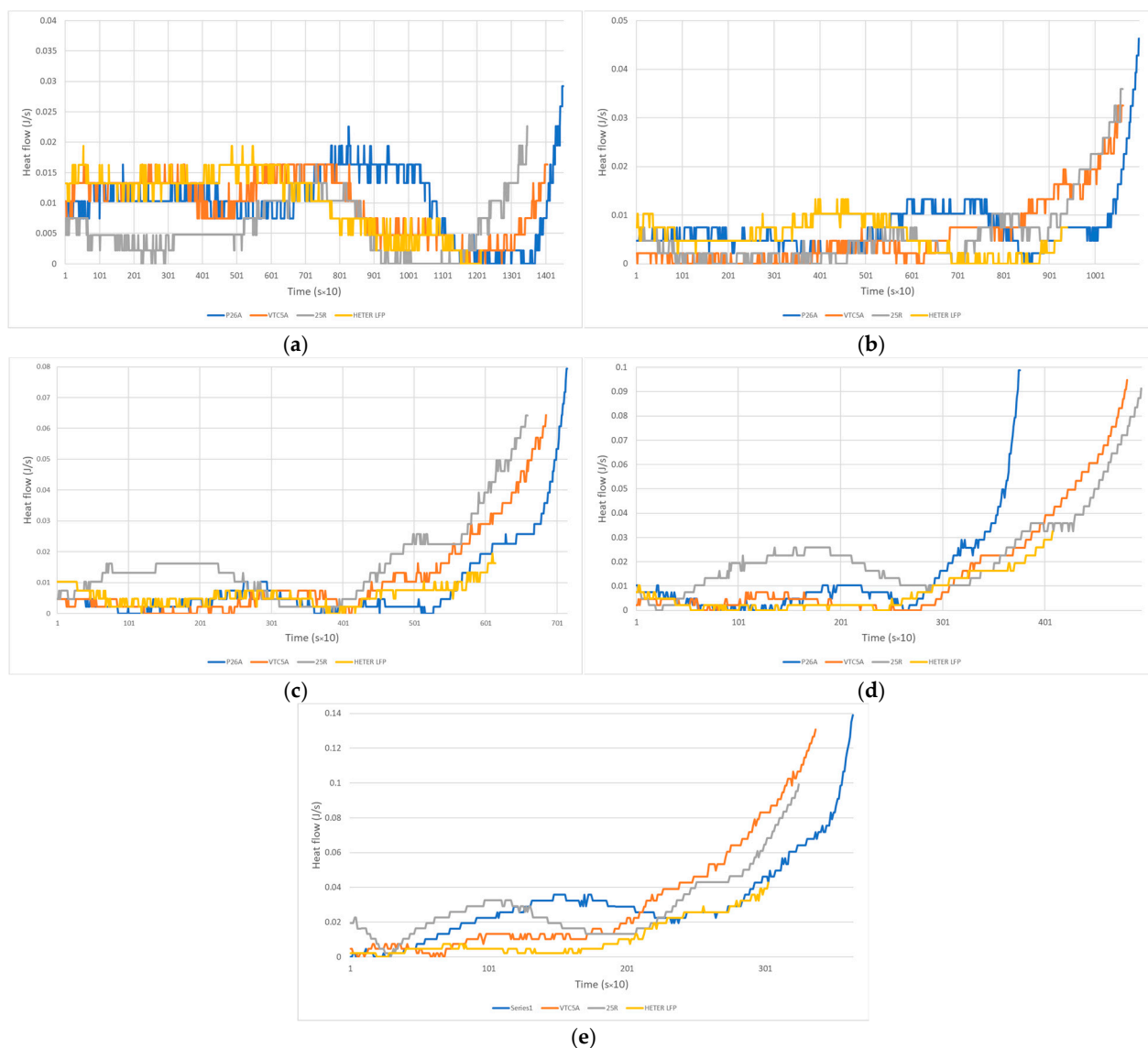


Figure 5. Heat flow of all cells during discharge at temperature of 40 °C, with discharging rates of (a) 0.25C, (b) 0.33C, (c) 0.5C, (d) 0.75C, and (e) 1C.

Discharging tests conducted at lower rates resulted in relatively low heat flow values throughout most of the testing period, with a characteristic increase toward the end of the test (Figure 5a–c). A clear separation between the heat flow curves of different cells was observed only at higher discharging rates of 0.75C and 1C (Figure 5d,e).

When comparing cell chemistries, both NMC and LFP cells exhibited similar behavior during discharging at lower rates. In these tests, NMC cells showed a noticeable increase in heat flow toward the end of the test, particularly evident in Figure 5c. The LFP cell did not display this end-of-test spike but maintained a steady linear to sub-linear increase in heat flow. At higher discharging rates (0.75C and 1C), the NMC cells exhibited

an exponential rise in heat flow near the end of the test, while the LFP cell showed a steeper, yet still linear, increase (Figure 5d,e).

The durations of the discharging tests were consistent with the expected times for each rate, as previously described. Slightly shorter durations were recorded for the LFP cell.

To summarize the observations from the discharging test at 40 °C:

- The behaviors of the cells were very similar to those in the test performed at 30 °C.
- The NMC cells showed an almost exponential rise in heat flow toward the end, due to increased internal resistance.
- The LFP cell showed a sublinear increase in heat flow, with some increase at the end—confirming more stable performance of this chemistry.
- Again, most of the heat was emitted in the period near the end of the test.

A clear trend observed during the discharging process was the progressive increase in heat flow as the test advanced, similar to the behavior seen in the discharging tests at 30 °C. Also, most of the total heat was emitted during the final 20% of the test duration.

With general interpretation of the results, we can conclude that the main driver of the heat generation are the charge and discharge rates (C-rates) caused by the cell's internal resistance and electrochemical inefficiencies, where discharging is more critical with peaks toward the end of the test. The LFP chemistry of Li-ion cells offers a thermal advantage, with lower heat dissipation and slower reactions, for application in confined spaces like underground mining environments. The main points are as follows:

- The most important parameter is the C-rate, that is, higher C-rates lead to higher heat flow. This trend was observed in all performed tests.
- Ambient temperature (30 °C and 40 °C) has minimal impact.
- LFP chemistry with lower heat flow and sublinear changes would be the preferred choice over NMC chemistry with more irregular heat flow fluctuations and higher heat flow.
- Rising heat flow at the end of the discharge test will probably result in operational procedures to prevent discharging below the final 20–15% of battery capacity.

An overview of the total heat emitted by each cell, categorized by cell type, test type (charging or discharging), and charging/discharging rate, is provided in Tables 1 and 2 for the testing temperatures of 30 °C and 40 °C, respectively. The total heat values were calculated according to the methodology described in Materials and Methods.

Table 2. Overall heat transferred to surroundings by the tested cells at 40 °C [J].

	40 °C									
	Charging					Discharging				
	0.25C	0.33C	0.5C	0.75C	1C	0.25C	0.33C	0.5C	0.75C	1C
P26A	-	76.95	113.13	129.84	130.68	147.78	80.89	62.46	44.74	113.31
VTC5A	45.14	84.56	111.82	160.98	133.39	135.25	65.36	75.19	80.33	105.34
25R	88.01	114.24	125.13	141.65	153.75	79.93	63.56	108.15	116.34	96.81
HETER	35.24	34.89	79.27	40.90	57.31	126.59	51.01	35.91	28.18	34.30

The results presented in the tables above confirm previously observed trends, such as the LFP cell (HETER) consistently emitted the lowest overall heat among all tested cells.

For the NMC cell P26A, the highest heat emission during charging at 30 °C occurred at the 0.75C rate. Under these conditions, the total heat emission ranged from 81.3 to 154.7 J, with the highest heat flow of 0.066 J/s recorded at the 1C rate. In comparison, during discharging at the same temperature, the highest heat flow was also observed at 1C (0.136 J/s), with total heat emission ranging from 56.84 J to 115.84 J. At 40 °C, the maximum heat

flow during charging was again at the 1C rate (0.064 J/s), and during discharging at the same rate (0.139 J/s). The highest overall heat emission during charging at 40 °C was 130.68 J (at 1C), which was surpassed during discharging at 0.25C, where the cell emitted 147.78 J—the highest value recorded in this research.

The VTC5A NMC cell did not show a consistent trend linking maximum heat flow to a specific charging/discharging rate or temperature. The highest heat flow during charging at 30 °C was 0.081 J/s (at 1C), and during discharging, 0.123 J/s (also at 1C). The overall heat emission was highest at 0.25C, with a value of 198.96 J, being the highest for this cell. Discharging tests at 30 °C yielded total heat emission between 63.83 J and 120.28 J (at 1C). This suggests that total heat emission is not strictly dependent on current rate when the charging/discharging cycle is completed fully (100%). The longer duration of low-rate tests compensates for the lower heat flow, balancing the total heat output. At 40 °C, the highest heat flow during charging was again at 1C (0.068 J/s), with total heat emission ranging from 45.14 J to 160.98 J (at 0.75C). During discharging, the total heat emission ranged from 65.36 J to 135.25 J (at 0.25C).

In total, 20 tests were conducted per cell—five charging and five discharging tests at two temperatures. In 10 of these 20 tests, the 25R cell produced the highest overall heat emission. The maximum heat flow recorded for this cell was 0.088 J/s during 1C charging at 30 °C, and 0.148 J/s during 1C discharging—the highest heat flow observed at 30 °C. At 40 °C, similar results were obtained, with the highest heat flows of 0.079 J/s (charging) and 0.099 J/s (discharging) both occurring at 1C. The total heat emission during charging at 30 °C ranged from 65.59 J (0.25C) to 189.54 J (0.75C), and during discharging from 50.09 J (0.33C) to 166.95 J (1C). Heat emission at 40 °C during charging tests ranged from 88.01 J (0.25C) to 153.75 J (1C), and during discharging from 63.56 J (0.33C) to 116.34 J (0.75C).

As previously noted, the HETER cell, the only LFP chemistry cell, consistently emitted the lowest heat in all tests. During charging at 30 °C, the highest heat flow was 0.034 J/s (at 1C), and during discharging, 0.052 J/s (also at 1C). At 40 °C, the highest heat flows were again at 1C: 0.036 J/s (charging) and 0.043 J/s (discharging). The total heat emission by the HETER cell was significantly lower than that of the NMC cells, ranging from 31.41 J (0.25C) to 62.43 (0.75C) during charging at 30 °C; 26.14 J (0.5C) to 50.35 J (1C) during discharging at 30 °C; 34.89 J (0.33C) to 79.27 J (0.5C) during charging at 40 °C; and 28.18 J (0.75C) to 126.59 J (0.25C) during discharging at 40 °C.

Now that all values of emitted heat have been established, the losses due to heat dissipation can be calculated using the method described above. These results are presented in Table 3 and illustrated in Figure 6.

Table 3. Heat losses (in %).

Temperature	Rate	P26A	VTC5A	25R	HETER
30 °C	0.25C	0.744	0.995	0.537	0.505
	0.33C	0.693	0.675	0.522	0.537
	0.5C	0.880	0.943	0.927	0.672
	0.75C	1.187	1.129	1.591	1.136
	1C	1.438	1.591	1.740	1.508
40 °C	0.25C	-	0.618	0.617	1.032
	0.33C	0.694	0.623	0.741	0.647
	0.5C	0.913	0.876	1.048	1.085
	0.75C	1.040	1.215	1.215	0.913
	1C	1.401	1.373	1.325	1.281

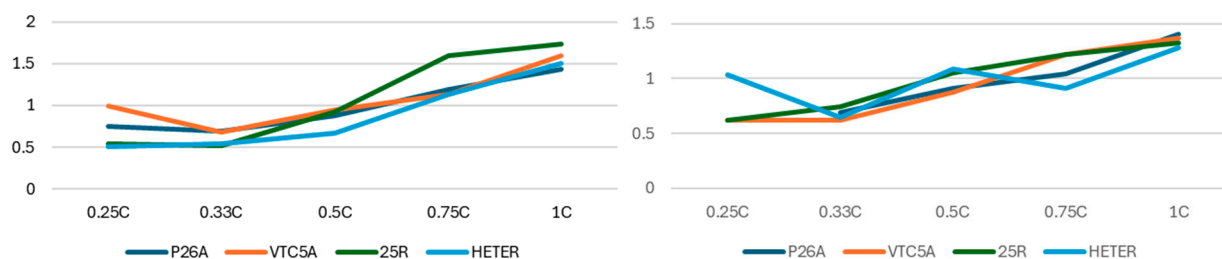


Figure 6. Heat losses (in %) for tests at 30 °C (left) and at 40 °C (right).

As shown, the heat losses for the P26A cell ranged from 0.693% to 1.438%. For the VTC5A cell, losses ranged from 0.618% to 1.591%, while for the 25R cell, they ranged from 0.522% to 1.74%. The HETER cell, the only LFP-based cell in the study, exhibited losses ranging from 0.505% to 1.508%.

A clear trend was observed: heat losses increase with higher charging and discharging rates. In some cases, losses increased by a factor of 2.5 to 3 as the rate increased. The results also indicate that cells tested at 40 °C and subjected to higher rates (0.75C and 1C) exhibited slightly lower losses compared to those tested at 30 °C. Conversely, at lower rates (0.25C, 0.33C, and 0.5C), tests at both temperatures indicated losses from 0.5 to 1%. However, these differences are relatively minor, suggesting that testing temperature has no significant impact on heat dissipation losses.

Finally, both NMC and LFP chemistries demonstrated similar efficiency, i.e., losses, without apparent difference—rising from 0.5% (at lower C-rates) up to 1.5% at 1C, with a maximum of 1.74% (NMC 25R at 1C).

4. Conclusions

This paper provides the results of testing four Li-ion cells under five charging and discharging rates at two ambient temperatures (30 °C and 40 °C), totaling 80 tests. Each cell underwent 20 tests—five charging and five discharging cycles at both temperatures. From another perspective, each rate was tested 16 times (charging and discharging of four cells at two temperatures).

The presented research on heat dissipation during charging and discharging of Li-ion cells under varying conditions highlights the differences between these two processes when all other parameters remain constant.

The main conclusion is that the testing temperature had no significant impact on losses due to heat dissipation. It is important to emphasize that the primary objective of this research is to estimate heat dissipation from Li-ion cells into the surrounding environment in confined spaces, such as underground mining operations—hence the selected temperature range. Ambient temperatures below 30 °C are generally acceptable in such environments, while those exceeding 40 °C are not.

Furthermore, the main cause of heat emission is the increase in charging and discharging rates. The maximum heat flow was observed at a 1C discharging rate. Notably, the highest heat flow during charging typically occurred in the middle of the test, whereas during discharging, it most often peaked at the end—frequently at the final measurement point. This pattern was especially pronounced at higher discharging rates.

The maximum heat emission occurred most frequently at the 1C rate, accounting for 44% of the tests (7 out of 16). The 0.75C rate followed with 25% (4 out of 16), while the 0.5C rate accounted for one test. The 0.33C rate did not have maximum heat emission in any condition. The 0.25C rate resulted in maximum heat emission in 4 out of 16 tests (25%). These results confirm that, generally, higher current rates lead to greater heat emission.

A comparison of heat emission during charging and discharging shows that the maximum was most often produced at the 0.75C rate (4 out of 8 tests), followed by 1C (3 out of 8) and 0.5C (1 test). During discharging, the maximum heat emission was again most frequently observed at 1C (4 out of 8), followed by 0.25C (3 tests), and 0.75C (1 test).

Across all tests, heat losses ranged from 0.505% to 1.74%. Higher charging/discharging rates consistently resulted in greater heat losses. In the context of underground mining, where ambient conditions are critical due to ventilation requirements, understanding battery heat loss in BEVs is essential, as it directly contributes to the ambient heat load. This research represents a first step in this direction, as BEVs and their associated infrastructure (e.g., chargers, power cables) also generate heat, further increasing the heat load in underground environments. Elevated heat and temperature levels can pose risks to both personnel and equipment operating in such conditions.

Supplementary Materials: The supporting information can be downloaded at: https://1drv.ms/f/c/7c5fcadb93bd414d/EvuytJ3yDa0Iv_IH6t9f0dkBrxlk1qv9jIWCJeR8X934Pg?e=GECKKs (accessed on 20th January 2026). This comprises Excel files with cell surface temperature and voltage measurements, grouped in folders according to testing temperature, charging/discharging rate and cell type.

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Abbreviations

Symbol	Nomenclature
$\dot{Q}$	Heat flow (J/s)
$\dot{m}_f$	Fuel consumption per rated power (L/kW)
E	Energy (kWs)
CV	Calorific value of fuel (kJ/L)
ρ	Average density of the battery (kg/m ³)
c	Average heat capacity of the battery (J/kg·K)
λ	Coefficient of heat conductivity of the battery (W/m·K)
$\dot{Q}_{conv}$	Convective heat flow (J/s)
$\dot{Q}_{lateral}$	Convective heat flow from lateral surface (J/s)
$\dot{Q}_{cover}$	Convective heat flow from cover surface (J/s)
ΔT	Difference between surface and ambient temperatures (K)
α_l	Coefficient of convective heat transfer from lateral surface ($\frac{W}{m^2K}$)

S_l	Lateral cell surface area (m ²)
α_c	Coefficient of convective heat transfer from cover surface ($\frac{W}{m^2K}$)
S_c	Cover cell surface area (m ²)
Nu	Nusselt number
λ	Thermal conductivity for given temperature ($\frac{W}{m \cdot K}$)
D	Cell diameter (m)
C'	Constant that depends on geometry, orientation, type of flow, boundary conditions and choice of characteristic length.
Gr	Grashof number
Pr	Prandtl number
n'	Constant that depends on type of flow (laminar or turbulent)
Pr_f	Prandtl number for fluid
Pr_A	Prandtl number for fluid, but for wall temperature
β	Coefficient of volume expansion (K ⁻¹)
g	Gravitational acceleration (m/s ²)
ν	Kinematic viscosity (m ² /s)
C_c	Constant of radiation (m ² ·K)
ε	Emission coefficient
S_{ef}	Effective surface of radiation (m ²)
C	Cell capacity (Ah)
U	Nominal cell voltage (V)
M	Cell mass (kg)

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