OPTIMIZATION RESEARCH ON THE COOLING OF LITHIUM BATTERY PACK FOR ELECTRIC MINI-TILLER
/
电动微耕机电池组的散热优化研究

Liang X.C. *, Huang S. [1]
Southwest University, College of Engineering and Technology, Chongqing Key Laboratory of Agricultural Equipment for Hilly and Mountainous Regions / P. R. China
Tel: 86-023-68251265; E-mail: dylb1978@swu.edu.cn
DOI: https://doi.org/10.35633/INMATEH-58-08

***Keywords:** Electric mini-tiller, battery cooling, orthogonal experiment, optimization*

ABSTRACT
The electric mini-tiller can produce extra heat during working, which leads to the problem that the span life of battery is shortened significantly. So, it is crucial to deduce the process of heat dissipation regarding batteries and show the simulations with Fluent. The data indicate that most of cells would generate the ideal temperature range under the natural condition, and thus the mode of forced cooling for batteries is imperative. In order to research the influence of different factors including the temperature, the velocity and the passage form of cooling liquid, an orthogonal experiment table has been designed and then the scheme of cooling is optimized. Compared with the control, the optimized outcomes imply that all cells are in the expected scope and the difference among cells is reduced obviously, extending the service life of batteries.

摘要
电动微耕机在作业过程中会产生明显的热量，将造成电池组寿命的过早衰退。推导了电池组的散热过程，使用 Fluent 软件仿真了电池的温度变化。数据表明自然散热下大多数电池单体的温度将偏离其最佳范围，因此需要采取强迫冷却。为分析冷却液体的速度、温度和通道对电池组散热的影响，设计了正交试验表，对电池组的散热方式进行了优化。结果显示电池组单体温度都在最优的范围内且不一致性明显降低，这将有助于延长动力电池组的寿命。

INTRODUCTION
The mini-tiller is driven by a gasoline or diesel internal combustion engine of 2~7.5 kW, weighs 50~150 kg and has a tilling depth of 10~16 cm. Because of the advantages such as being multifunctional, small in size and light weight, it is one of the most popular agricultural machinery equipment in the hilly and mountainous regions.

Recently, the disadvantages of the mini-tiller have been noticed by the researchers. For example, intense vibration produced by the mini-tiller may result in neurological disorder and organ damage *(Li et al., 2016)*. In addition, these defects also cause severe injuries even death *(Fabbri A., et al., 2017)*. Aiming at these shortcomings, some studies have been fulfilled. The majority of the vibration is from the engine and the vibration effect of different fuels must be considered *(Heidary B. et al., 2013*). Parts of the vibration are generated during the tilling process and the geometry of blade and the scoop angle characteristics of a handheld tiller's rotary blade has been explored *(Zhang Y. H. et al., 2016)*. For cutting off transfer of vibration, pre-stress means are adopted to analyse the vibration of the mini-tiller, and the consistency between theoretical outcome and test data has been achieved *(Wang Z. et al., 2018)*. Although such studies are beneficial to enhance the performance of mini-tiller, it is tough to eliminate those deficiencies. Considering the structure characteristic of mini-tiller—all components have been installed under the rigid mode, replacing the gasoline internal combustion by an electric motor may be feasible to boost its operating properties *(Liang X. C. et al., 2018).*

The electric mini-tiller has several advantages such as light weight, low noise and zero emission, and thus it can meet the needs of modern agriculture development. Although the electric mini-tiller has some advantages, yet unwanted performance of the apparatus is hard to be ignored.

---
[1] *Liang X.C., Ph.D. Eng.; Huang S., Ms. Stud. Eng.*

Specifically, when the electric mini-tiller is working, extra heat will be generated by the batteries. It is well known that the energy system of electric mini-tiller is made up by a number of cells; the difference among cells will be enlarged if the thermal energy fails to be dissipated rapidly, leading to add difficulty on managing their heat.

It is crucial to keep the batteries under the ideal temperature range, which is constructive to extend the span life of cells. Relevant published papers have demonstrated how to control the temperature of battery. In order to improve the performance, the modelling method to battery thermal analysis is proposed and thermal characteristic and influence law have been confirmed *(Li J., et al., 2016).* In fact, cooling fluid is vital to the service life of battery, so a working medium is researched in both theoretical analysis and experimental research *(An Z. et al., 2018)*. The working condition is associated with the thermal energy, so the typical situation may be more valuable to be explored regarding temperature rise *(Guo Y. et al., 2018)*. The adaptable algorithm can strengthen the cooling effect and a greedy algorithm is simulated *(Chen K. et al., 2018).* In essence, heat produced appears from the chemical reaction during battery working and it is imperative to conduct some research on these settings *(Zhu H. et al., 2018)*.

The electric mini-tiller is a new thing for the majority of operators, and inadequate experiments have been done. It is well known that lithium battery is main component of storing energy for most of agricultural apparatus, but few experiments focused on thermal analysis have been completed, which is related to the span life of lithium battery. In fact, the mini-tiller's working conditions are distinctly different to the vehicles, so thermal analysis of the battery should be completed according to the operating condition of mini-tiller, and thus the service life of batteries can be enhanced notably.

MATERIALS AND METHODS

For the sake of temperature issue solving satisfactorily, it is valuable to research the process of heat dissipating during electric mini-tiller working. An elementary prototype shown in Figure 1 has been designed by the author and his students, and the concerned analysis is focused on the tiller.

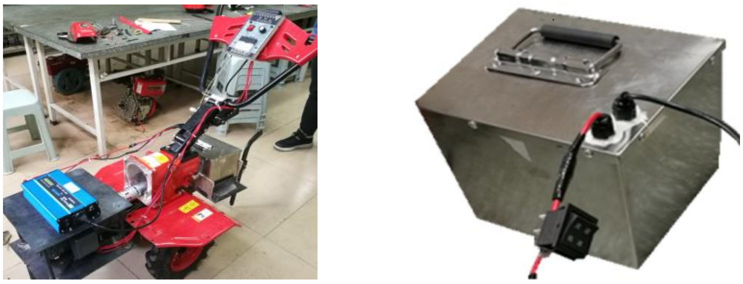


Fig. 1 - Electric elementary prototype and battery box

Compared with the traditional mini-tiller, the manufacturing cost of the prototype is huge. In order to decrease the cost, the capacity of battery and the power of electric motor are both smaller than the computing outcome, verifying the feasibility of the prototype. The main parameters are listed as below.

Table 1

Specification of the prototype

Mini-tiller item	**Parameter**
Motor type	Direct current motor
Electric motor power [kW]	0.75
Related rotation speed [r/min]	1800
Battery type	Li-NiCoMn lithium ion battery
Battery capacity [$A \cdot h$]	20
Cooling mode	Air cooling

When the cell is regarded as a whole, heat produced inside of cell is transferred from the inner to outer layer through conduction and it is calculated with the formula

$$\dot{q} = -\lambda gradT \tag{1}$$

Where: $\dot{q}$ is the vector of heat flux, [W/m^3]; λ is the thermal conductivity coefficient, [$W/(m.k)$];

T is the temperature, [K]; $grad$ is the temperature gradient, [$k \cdot m^{-1}$];

"—" is minus which means that the gradient direction is the direction of temperature rising.

If the air passes the surface of battery, part of the heat is dissipated by convection means, and such heat exchange is calculated as follows:

$$Q_v = hA(T_m - T_f) \tag{2}$$

Where :

Q_v is the convection heat, [J];

h is the coefficient of convection heat, [W/m^2];

A is the area of convection heat, [m^2];

T_m is the surface temperature of battery, [K];

T_f is the temperature of liquid, [K].

Except heat conduction and convection, part of heat is escaped from battery by radiation, and it can be expressed as:

$$P_r(T) = \varepsilon\sigma\left(T^4 - T_s^4\right) \tag{3}$$

Where:

P_r is the power of heat radiation, [W/m^2]; ε is the radiation coefficient;

σ is the Stefan-Boltzmann constant, σ=5.67×10^{-8},[$W/(m^2\cdot K^4)$];

T_s is the environmental temperature, [K].

Using the formula (1) ~ (3), it is not difficult to compute the thermal variation of a cell under a certain fringe condition, while it is tough to get accurate results based on complex boundary conditions for a battery pack. Hence, applying professional tools for results is necessary.

The process modelling of lithium battery is described in some following steps. Firstly, battery pack is designed with SolidWorks. Secondly, considering the structure trait of cell, structured meshes shown in Figure 2 are made with ICEM CFD. In addition, the air computational domain is drawn with unstructured meshes so that the workload is simplified remarkably. Last, the calculating program will be launched after initializing the parameters.

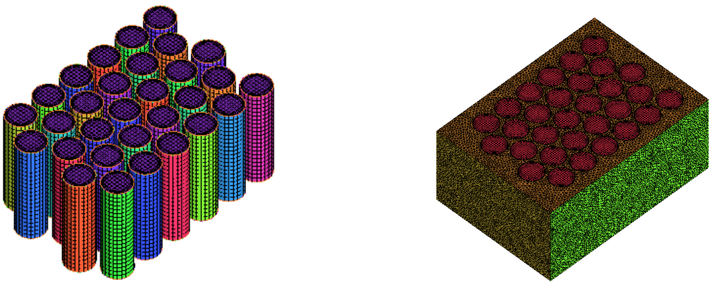
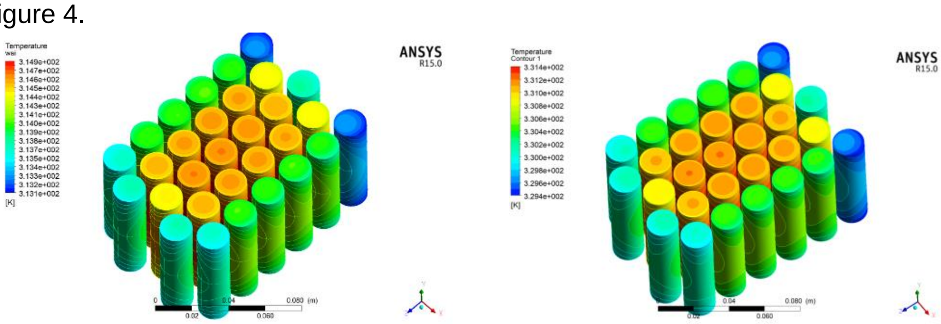


Fig. 2 - Electric elementary prototype and battery box

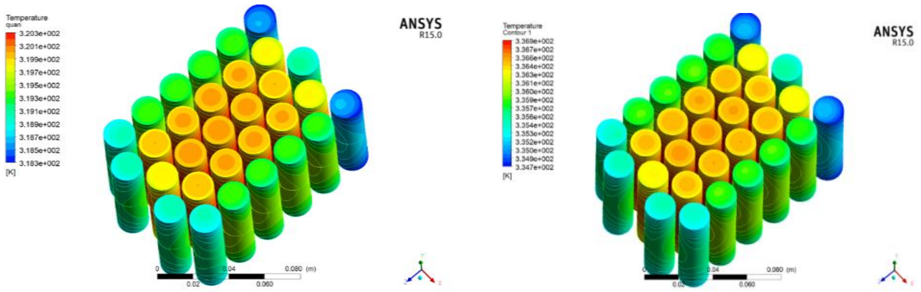
RESULTS

According to the rule of software, parameters such as material property, solver and initial value are fulfilled in turn. Evidently, the battery pack is sealed in the box shown in Figure 1, and thus it is reasonable to assume the boundary of air domain has constant temperature. When the discharging rate is set in 3C and 4C, and the surrounding temperature is designed under 25°C and 40°C, simulations are expressed in figure 3 and figure 4.



a) rate=3C and T=25° C b) rate=3C and T=40° C

Fig. 3 - Simulation results under different discharging rate and temperature



c) rate=4C and T=25 ºC d) rate=4C and T=40 ºC

Fig. 4 - Simulation results under different discharging rate and temperature

In practice, the tilling condition is complicated and it is hard to sustain the rated discharging rate for battery pack. Considering the compact space of the electric tiller, the battery pack will be operated under big discharging rate, and the heat generated cannot be neglected. As it can be observed from figure 3 and figure 4, it is easy to find the discharging rate and the surrounding temperature which are related to the highest temperature of cells. The bigger discharging rate is, the higher the temperature will be, and so will the environmental temperature. In addition, cells in the central position of battery pack are rather higher in temperature than those in the outer layer. The reason lies in the fact that the cells located in the centre area only have two surfaces to exchange heat, but the other cells have more surfaces to dissipate heat.

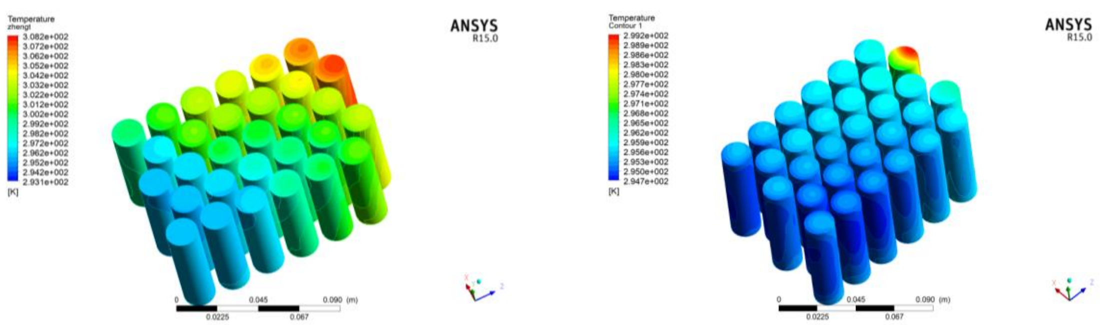
For most types of lithium battery, keeping temperature in the range from 25ºC to 40ºC is advisable, extending their span lives in a way, while in figure 3 and figure 4 the highest temperature is over 50ºC for some cells. If the heat accumulated is enormous, severe accidents such as spontaneous burning even explosion will emerge. Briefly, the challenge is to keep the battery in the ideal temperature range under the natural condition. Therefore, it is natural to deal with this problem using other means. The specific capacity of hydraulic medium is far larger than that of gas, so forced cooling with fluent is valuable to solve that issue. A kind of transformer oil possesses some traits including low viscosity, good conduction, big specific capacity and notable insulation, so it is adopted as a cooling medium, and parameters are listed in Table 2

Table 2

Specification of the transformer oil

Transformer oil	**parameter**
Density [$kg \cdot m^{-3}$]	960.6
Specific capacity [$J \cdot kg^{-1} \cdot K^{-1}$]	1510
Thermal coefficient [$W \cdot m^{-1} \cdot K^{-1}$]	0.157
Dynamic viscosity [$kg \cdot m^{-1} \cdot s$]	0.00384

Similarly, it is easy to obtain simulations under the forced convection mode. For getting the practicality of the cooling system, the discharging rate is set at 6C which is as two times as the former one. The surrounding temperature is 25ºC and the initial temperature of fluent is 20ºC. In order to test the relation between fluent velocity and cooling effect, the velocity is designed at 0.006 m/s and 0.01 m/s. The simulations are showed as follow.



a. 0.006m/s b. 0.01m/s

Fig. 5 - Simulations under different velocity of cooling fluent

As it can be observed from Figure 5, the maximum temperature is 35°C and the minimum temperature is 20°C, which indicates fluent cooling is more effective than natural cooling. Although the working temperature of all cells is in the ideal range, the highest temperature difference is 15°C, which is harmful to the service life of cells; the difficulty of heat managing will be added as well. It is a common sense that higher fluent velocity will consume more energy, while tilling time can be shortened distinctly. Hence, how to keep the balance of battery's temperature and operating time of tiller should be researched deeply.

Several factors including surrounding temperature, fluent velocity, passage form, specific capacity and others are associated with the cooling effect *(Zhang X., et al., 2011)*, and such the conclusion is beneficial to resolve cooling problem of lithium battery as well. So, a scheme of optimum design has been made in Table 3, and the passage form is illustrated in Figure 6.

Table 3

The scheme of optimum design

No. \ Factors	A v_{cool}	B T_{cool}	C $Pass_{form}$
	m/s	K	-
1	0.01	15	3 passages
2	0.01	25	2 passages
3	0.01	20	1 passage
4	0.006	15	1 passage
5	0.006	25	2 passages
6	0.006	20	3 passages
7	0.002	15	2 passages
8	0.002	25	1 passage
9	0.002	20	3 passages

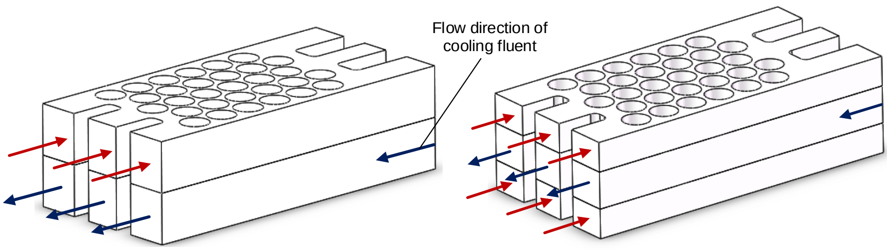


Fig. 6 - Passage form of fluent medium

If the lithium battery is expected to realize the longest service life, the maximum temperature should be in the ideal range and the temperature difference should remain at 0°C. Therefore, results are focused on the range analysis including the sum of data, the average of levels and the range of mean level. Compared with different test data, the optimal combination among experimental factors can be confirmed. The test results are shown in the Table 4.

Table 4

The test results

No. \ Factors	A v_{cool}	B T_{cool}	C $Pass_{form}$	T_{max}	T_{dif}
	m/s	K		K	K
1	1	1	1	295.53	3.22
2	1	2	2	304.57	3.91
3	1	3	3	299.19	4.53
4	2	1	3	295.91	3.85
5	2	2	1	305.39	4.05
6	2	3	2	302.05	7.00
7	3	1	2	304.56	10.39
8	3	2	3	311.69	10.25
9	3	3	1	306.70	6.65

Obviously, the highest temperature of battery is in the expected range, while the temperature difference among cells is unacceptable. Indeed, if the lithium cells are kept in such working mode, the property of whole battery pack will be worsened because of the Buckets effect. In addition, the span life of partial cells would be shortened greatly. In a word, the test results are imperfect and further research should be conducted. In order to verify the primary-secondary relationship of experimental factors, the concerned data is gathered in Table 5. It is not difficult to know the relationship between the experimental factors and cooling effect, and the optimal combination is confirmed.

Table 5

The range analysis on the highest temperature

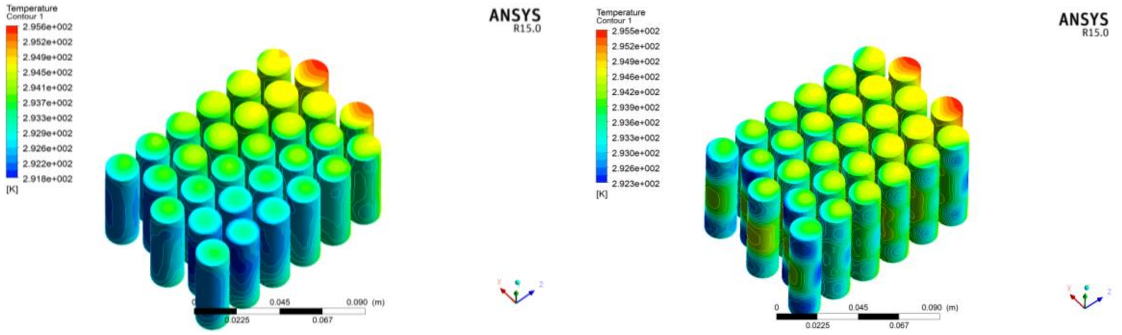
Factors / Range	A v_{cool}	B T_{cool}	C $Pass_{form}$
K_{1j}	899.29	896.00	907.62
K_{2j}	903.35	921.65	911.18
K_{3j}	922.95	907.94	906.79
k_{1j}	299.76	298.67	302.54
k_{2j}	301.12	307.22	303.73
k_{3j}	307.65	302.65	302.26
R_j	7.89	8.55	1.46
Master-subordinate relation of factors	$B>A>C$		
Optimal combination	$A_1B_1C_3$		

Except for the highest temperature, the thermal difference among cells is associated with achieving the satisfied service life of battery pack. The less the difference is, the better the battery performance will be. Therefore, it is crucial to control the cells working on the same temperature. Similarly, the range analysis on the temperature difference based on the cells is represented in the Table 6, and the optimal scheme can be obtained. To illustrate the availability of optimal combination, related results regarding the highest temperature and thermal difference are showed in Figure 7.

Table 6

The range analysis on the temperature difference

Factors / Range	A v_{cool}	B T_{cool}	C $Pass_{form}$
K_{1j}	11.66	17.46	13.92
K_{2j}	14.90	18.21	21.30
K_{3j}	27.29	18.18	18.63
k_{1j}	3.89	5.82	4.64
k_{2j}	4.97	6.07	7.10
k_{3j}	9.10	6.06	6.21
R_j	5.21	0.25	2.46
Master-subordinate relation of factors	$A>C>B$		
Optimal combination	$A_1B_1C_1$		



a) highest temperature b0 temperature diffierence

Fig. 7 - The nephogram of temperature

From Figure 7a, the working temperature of cells is settled in the range from 18 to 22 ºC, and the biggest difference is 4ºC. While in the other cooling scheme, the temperature scope is 19 to 22 ºC, and the greatest difference is 3ºC in Figure 7b. Although the cooling effect of two combinations is extremely proximate, the master-subordinate relation of experimental factors is different. Obviously, keeping two optimization plans for the battery pack is not feasible, reducing the cost of the electric mini-tiller, so the sequence of test factors should be given solely.

In two schemes, the factor A is listed in the second and first position, respectively. Factor B is arranged in the first and third order, relatively. In the case of factor C, it is settled in the third and second position, individually. Considering the highest temperature and thermal difference are vital to the battery pack, the ultimate primary-secondary sequence is $A > B > C$ and the optimal combination of test divisors is $A_1B_1C_1$.

Though the master-subordinate rank of experimental factors can be verified from the range analysis on simulations, it is hard to ensure whether the effect of the factors based on the indicators is valid or not. When the experimental error of data is large or the required precision is high, it is a good choice to use variance analysis to verify the reliability of the conclusion.

In the variance analysis of test data, several parameters such as sum of deviation squares, degree of freedom, significance testing must be calculated. The sum of dispersion squares is computed as

$$S_j = r\sum_{h=1}^{m}(k_{hj} - \bar{y})^2 \tag{4}$$

Where:

k_{hj} is the h level mean value in the j column;

r is the number of h level replication;

$\bar{y}$ is the mean of test outcome.

For the whole data, the total sum of dispersion squares is

$$S_{tot} = \sum_{i=1}^{n}(k_i - \bar{y})^2 \tag{5}$$

Where:

k_i is each test record;

S_{tot} is the total sum of deviation square.

The degree of freedom can be counted as

$$f_j = m_j - 1 \tag{6}$$

Where:

m_j is the number of levels in the j column;

f_j is the degree of freedom in the j column.

Then the total degree of freedom can be written as

$$f_{sum} = n - 1 \tag{7}$$

Where:

n is the count of experiment.

At the same time, the significance testing can be calculated as

$$\bar{S}_j = S_j / f_j \tag{8}$$

The test data have been calculated from the perspective of variation analysis, which is shown in Table 7. Compared to Table 5, the conclusion is quite identical. That is to say, test factor A and B are strongly related with the cooling effect, while factor C has less influence to the results.

Table 7

The variation analysis of highest temperature

Source of variation	quadratic sum	Degree of freedom	Mean square	F value	Significance level
A	106.72	2	53.36	116.75**	0.01
B	109.83	2	54.91	120.15**	0.01
C	3.63	2	1.81	3.97(*)	0.25
Error	0.91	2	0.46	—	—
Sum	221.09	8	$F_{0.25}(2,2) = 3.00$; $F_{0.01}(2,2) = 99.01$		

Similarly, the data can be analysed in Table 8. It is easy to conclude that the calculated outcome is the same to table 6, which expresses that the former results are reliable.

Table 8

The variation analysis of thermal difference

Source of variation	Quadratic sum	Degree of freedom	Mean square	F value	Significance level
A	45.37	2	22.68	6.83(*)	0.25
B	0.12	2	0.06	0.02	—
C	9.31	2	4.65	1.4	—
Error	6.64	2	3.32	—	—
Sum	61.44	8	$F_{0.25}(2,2)=3.00$; $F_{0.1}(2,2)=9.00$		

CONCLUSIONS

- Forced cooling is vital to keep the battery in the suited temperature, and life span of cells can be guaranteed regardless of any tilling conditions.
- The velocity and temperature of cooling liquid have much stronger influence on thermal controlling regarding cells than that the passage form does.
- Part of electric energy has been consumed on battery cooling, so the tilling time may be shortened. Hence, how to decrease the consumption rate should be further researched in the future.

ACKNOWLEDGEMENT

This paper was financially supported by the Fundamental Research Funds for the Central Universities (No. XDJK2016B025) and the Doctoral Fund of Southwest University (No. SWU115022).

REFERENCES

[1] An Z. J., Jia L., Yang C. L., et al, (2018), Experimental investigation of lithium-ion power battery liquid cooling vehicle. *Automotive Engineering*, vol.35, issue 2, pp.254-260;

[2] Chen K., Wang S. F., (2018), Optimization of thermal management system for lithium ion battery based on three-dimensional thermal coupling model. *Journal of Engineering Thermophysics*, vol.39, issue 5, pp.1092-1096;

[3] Fabbri A., Cevoli C., Cantalupo G., (2017), A method for handlebars ballast calculation in order to reduce vibration transmissibility in walk behind tractors, *Journal of agricultural engineering*, XLVIII:599, pp.81-87;

[4] Guo Y. D., Li Y.F, Zhang W. H., et al, (2018), Research on temperature performance of power battery under typical condition. *Chinese Journal of Power Source*, vol.42, issue 8, pp.1143-1146;

[5] Heidary B., Hassan-beygi S.R., Ghobadian B., (2013), Investigating a power tiller vibration transmissibility using diesel-biodiesel fuel blends on stationary conditions, *Journal of mechanical Engineering and technology,* vol.5, issue 1, pp.19-31;

[6] Liang X. C., Chen J., Wang Z., (2018), Research on the vibration of mini-tiller. *INMATEH Agriculture Engineering*, vol.56, issue 3, pp.17-24;

[7] Li G., Chen J., Xie H. J., Wang S. M., (2016), Vibration test and analysis of mini-tiller, *Int J Agric. & Biol. Eng*., vol.9, issue 3, pp.97-103;

[8] Li J.Q., Wu P. E., Zhang C. N., (2016), Study and implementation of thermal management technology for the power batteries of electric vehicle. *Automotive Engineering*, vol.38, issue 1, pp.22-27;

[9] Wang Z., Chen J., Wang S. M., Niu P., Hu C. J., Wang Y. L., Zheng Y.L., (2018), Simulation and experimental study on the vibration response of the pre-stressed mini-tiller handle. *Journal of Agricultural Mechanization Research*, vol.40, issue 4, pp.195-199;

[10] Zhang X. W., (2011), Thermal analysis of a cylindrical lithium-ion battery, *Electrochimica Acta*, vol. 56, issue 3, pp.1046-1055;

[11] Zhang Y. H., Yang L., Niu P., Li S. T., Xie S. Y., Chen X. B., Yang M.J., (2016), Study on the scoop angle characteristics of a handheld tiller's rotary blade, *INMATEH Agriculture Engineering*, vol.49, issue 2, pp. 5-12;

[12] Zhu H., Wang W.Q, E J.Q. et al, (2018), Optimization of thermal management system for lithium ion battery based on three-dimensional thermal coupling model. *Chinese Journal of Power Source*, vol.42, issue 4, pp.497-500.