EXPERIMENTS ON PADDY DRYING MECHANISM OF FAR-INFRARED CONVECTION COMBINATION IN COMBINE HARVESTER
/
联合收割机中对流远红外联合稻谷在机干燥机理试验研究

Chen P.L.[1,2], Xu J.[*1,2], Tang Y.[1], Liu M.H.[1,2]
[1] College of Engineering, Jiangxi Agricultural University, Nanchang/China; [2] Key Laboratory of Modern Agricultural Equipment, Jiangxi Province, Nanchang/China;
Tel: +8613979166680; E-mail: xujing0085@163.com
DOI: https://doi.org/10.35633/inmateh-59-15

Keywords*: grain dying; infrared; hot air; combine harvester*

ABSTRACT
In order to acquire the coupling mechanism of the paddy flow, hot air and far-infrared radiation, an experiment bench based on the screw conveyor and grain collecting tank of combine harvester was set up, and then the orthogonal experiment with six factors and five levels was conducted using the dehydration rate (DR), increased crack percentage (ICP) and specific energy consumption (SEC) as indexes. The optimal combination of factors for each index was acquired and the experiment results show: the drying combination could achieve rapid drying with good drying quality and low energy consumption; the initial water content of paddies is the dominant factor for the DR, ICP and SEC; the hot air has more effect on the drying performances compared with the IR radiation.

摘要:
为了获取谷物流、热风和远红外场的耦合机理，以联合收割机的搅龙和收粮箱为基础，搭建了远红外热风联合干燥实验平台，以干燥速率、爆腰增率以及单位能耗为目标，进行了六因素五水平正交实验，获取了各实验目标最优的因素组合，实验结果表明：该嵌入联合收割机中的组合干燥系统能够实现快速、高质以及低能耗干燥；水稻的初始含水率是影响干燥速率、爆腰增率以及单位能耗的主要因素；相比于红外辐射，热风对干燥性能具有更大的影响。

INTRODUCTION

The widely using paddy combine harvester significantly reduces the harvest time of paddy; moreover, the paddy should have high moisture when it is harvested in order to decrease the loss of it. Harvesting the high moisture paddy rapidly makes the grain-sunning ground not big enough for farmers to dry paddy efficiently, and thus many farmers lay out the paddy on the road or highway which may seriously affect traffic in China. Meanwhile, farmers' use of sun drying totally depends on the weather; they have to stack the wet paddy at home and if there is continuous rainy weather, mildew appears. Although the stationary drying machine has been used since 2004 in China, it is inconvenient for the hilly area because of the excess carriage expense and energy consumption.

One solution to solve the problems above is to design a combine harvester with the function of grain drying simultaneously, and the drying system should be energy-saving and quick-drying to synchronize the harvest speed of combine harvester. Many works have been done to reduce the energy consumption of the drying system such as optimizing the drying process, taking the new heating device, recycling the exhaust heat and so on (*Niu X.H., Cao C.W., 1999; Chen K.J., Chen Q.C., Zhang Y., 2005*). Since the cooling water and exhaust gas takes away more than 60% of fuel energy of diesel engine equipped on the tractor and combine harvester, recovering the waste heat of diesel engine to dry grain has been the concern of many researchers. Bai et al. *(Bai J.W., Luo S.Q. et al., 2008)* equipped a semi-drying system on a tractor powered by the waste heat, and their drying system could decrease the grain water content by 3 to 6 percent. Fei et al. *(Xiang F., Wang L., Yue X.F.,2011)* developed a vehicle-mounted heat pump–assisted fluidization drying system driven by the waste heat recovered from the jacket water of diesel engine and flue gas of the drying system; their analysis results showed that the actual specific diesel consumption can reach 0.081 [(kg diesel)/(kg water)].

The hot air drying is often used for the method of recycling the heat waste of agricultural machinery to dry grain, and it usually requires a long period of drying time and a large amount of thermal energy *(Celma R.A., Rojas S., Lopez-Rodriguez F., 2008*); hence, it is not suitable for drying grain directly on the combine harvester because of the high harvest speed. To overcome the drawbacks of the hot air drying, infrared radiation has been integrated with it. Far-infrared convection combination drying is widely used for foodstuffs such as corn *(Rahmanian- Koushkaki H., Nourmohamadi-Moghadami A., Zare D. et al., 2017)*, rice (*Sarobol M., Teeta S., Pharanat W. et al., 2018)*, potato (*Onwude D.I., Hashim N., Abdan K. et al., 2019*) and so on. In contrast to pure hot air drying, the combined technique was found to accelerate heat and mass transfer, leading to a shorter drying time and better drying quality *(Liu C.S., Shang T., Yang S.Q., 2017; Zare D., Naderi H., Ranjbaran M., 2015).*

Noting far-infrared convection combination can not only use the waste heat of combine harvester but also dry grain quickly with less damage to its quality, the new drying system equipped with far-infrared and supplementary hot air could dry paddy directly in the drying chamber embedded on the screw conveyor and grain collecting tank of combine harvester was proposed. Then a test bench was setup to acquire the coupling mechanism of paddy flow, hot air and far-infrared using the orthogonal test.

MATERIALS AND METHODS

EXPERIMENT BENCH

The experiment bench designed is shown in Fig.1. A hot air blower pushes the hot air into the screw conveyor and grain collecting tank of combine harvester, and the hot air from the hot air blower simulates the hot air heated by the waste heat of combine harvester. The air temperature and velocity can be regulated by the voltage regulator 1 and the throttle, the actual air temperature and velocity can be detected by the air temperature and velocity sensors. Infrared (IR) radiator *1* and IR radiator *2* are embedded in the walls of screw convey and grain collecting tank and their powers can be regulated by the voltage regulator *2* and *3*. The paddy is put into the hopper, and the screw conveyor driven by the motor promotes the paddy into the grain collecting tank. The paddy is dried by the hot air and far IR radiators.

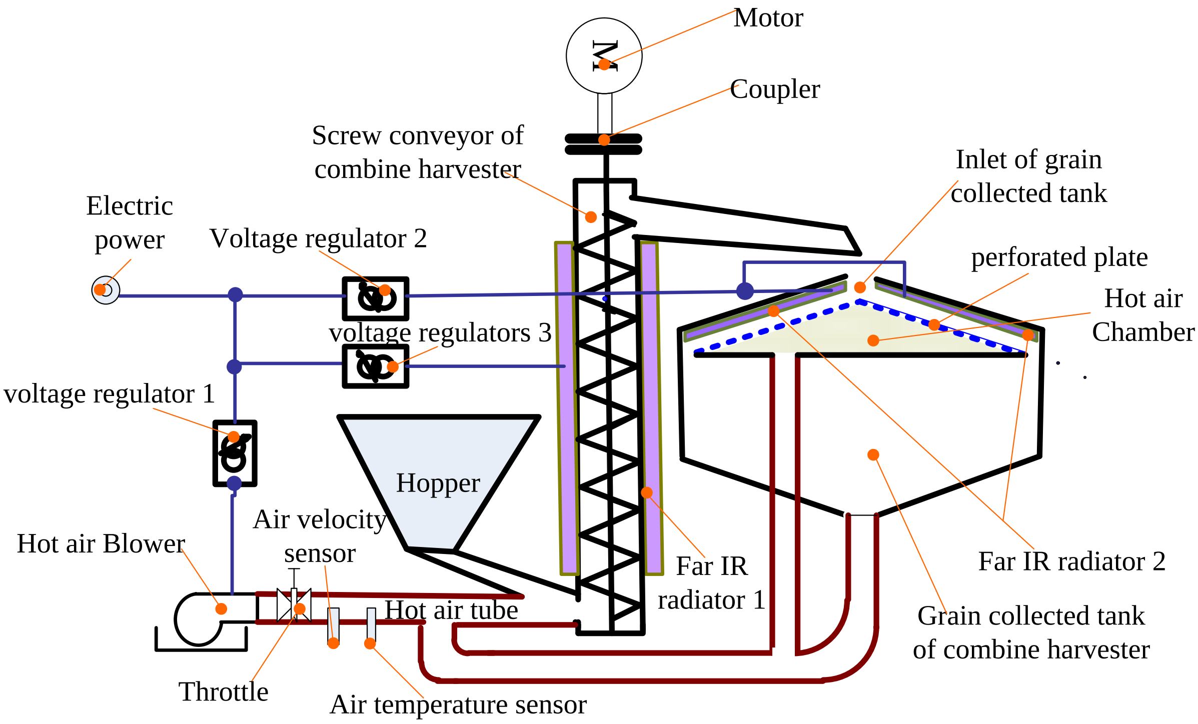

Fig. 1 - Layout of the experiment bench

In order to simulate the actual working process, the hot air blower is started and the air pushed by it is conditioned to a suitable velocity and temperature to preheat the bench for about 3 to 5 min before the experiment, and then the paddy to be dried is added to the hopper and is stuffed up by a strikerplate to prevent it from rushing into the screw conveyor of the combine harvester. Only when the parameters of far IR radiator *1*, far *IR* radiator *2* and the hot air blower are adjusted to the pre-set values according to the test arrangement, can the strikerplate be opened. Then, the paddy flows to the screw conveyor and is dried by the far IR radiator *1* combined hot air while the paddy is promoted by the screw convey. A pipe connects the outlet of screw conveyor and inlet of the grain collecting tank of combine harvester and it forms a tempering period of dried paddy. After tempered, the paddy is homogeneously dispersed on a perforated plate, and the thin-layer paddy is dried by the far IR radiator2 and the hot air penetrated from the holes in the perforated plate.

The parameters of hot air blower are listed in Tab.1.

Table1

Hot air blower technical parameters

Parameter	value	Parameter	value
Supply voltage [V]	380	Blower power[kW]	0.75
Outlet air pressure [Pa]	1500	Blower speed [r.min-1]	2800
Max air flux [m3.h^{-1}]	1320	Max air temperature[K]	623K
Heating Power [kW]	6		

The voltage regulators are made by Shanghai Nenggong Electronic CO., LTD, P.R. China, and their model number is NG3A-30A.

EXPERIMENT MATERIALS

The paddy for the experiment is the late paddy of 2018 and it comes from the experimental field of Jiangxi Agricultural University. In Fig.2 is the paddy to be dried. Impurities had been removed from the paddy and it was grouped; then, each group underwent the conditioning treatment according to the reference (*Li C.L., 2004*) to attain different water contents.

Fig. 2 - Paddy to be dried

EXPERIMENT METHOD

The purpose of the experiment is to acquire the influence laws of energy distributions on the drying performances and energy consumption under different harvest conditions. The orthogonal method is adopted to solve this multi-factor and multi-object problem because of its effectiveness, scientificity, convenience and economy. The orthogonal method can reduce workload and experiment cost compared to the comprehensive test method, especially for the multiple-factor and multiple-level experiment.

Factors and levels. The factors and levels are listed in Tab.2. Since the higher the hot air temperature is, the more the paddy rice cracks, the hot air temperature range is set as 40°C-60°C (*Wang J.H., 2000*). The ranges of hot air velocity (HAV), the speed of screw conveyor(SSC), the power of IR radiator 1(PIR1) and the power of IR radiator 2(PIR2) are set as 4 m/s-5.3 m/s, 264r/min-288r/min, 1kW-3kW and 3kW-5kW respectively according to the reference (*Kuang P., 2016*). The initial water content (IWC) of paddy could vary from 18% to 28%.

Table 2

Factors and levels

Factors / Levels	HAT [°C]	HAV [m/s]	SSC [r/min]	PIR1 [kW]	PIR2 [kW]	IWC [%]
1	40	4.00	276	1	3	20
2	45	4.10	270	1.5	3.5	18
3	50	4.95	282	2	4	22
4	55	4.66	264	2.5	4.5	24
5	60	5.30	288	3	5	28

Orthogonal table. According to the number of factors and levels, the orthogonal table$L_{25}5^6$ is adopted without concerning the interactions of factors.

Experiment indexes. There are three indexes including dehydration rate (DR), increased crack percentage (ICP) and specific energy consumption (SEC). The DR is the index of the drying speed and it can be expressed as:

$$v_t = \Delta w / \Delta t \tag{1}$$

where v_t is the average dehydration speed [%/min]; Δw is the changes in water content before and after drying [%]; Δt is the drying time [min].

The ICP is the index of drying quality and it could be acquired abiding by the following steps:

(1) The paddy is sampled and packaged after drying and returning to the indoor temperature;

(2) After packaged for 48 hours, 150 g paddy is taken out by random sampling and divided into three groups as shown in Fig.3;

(3) The paddy of each group is carefully hulled by hand as shown in Fig.4, and then the hulled paddy is checked with a magnifying glass to obtain the crack ratio;

(4) The mean value of three groups' crack ratio is the final crack ration, and increased crack percentage of the final crack ration after and before drying is the ICP (*Dhib R., Broadbent A.D., Thérien N., 1994*).

Fig. 3 - Dried paddy sample

Fig. 4 - Hulled paddy

The SEC is the heat consumption per water dehydrated, and it can be calculated as:

$$q = Q / W \tag{2}$$

Where, q is the SEC [kJ/kg.H_2O]; Q is the total heat consumption [kJ]; W is the water dehydrated [kg], and it can be expressed as:

$$W = G - G_0 \tag{3}$$

Where, G and G_0 are the paddy weight [kg] into and outside the drying system respectively;
According to the law of conservation of mass, we can acquire:

$$G\ (1-w_1)\ = G_0\ (1-w_0) \tag{4}$$

Where, w_1 and w_0 are the water content of paddy [%] after and before drying respectively; combining Eq.3 with Eq.4, W can be expressed as:

$$W = \frac{G\left(w_1 - w_0\right)}{1 - w_1} \tag{5}$$

RESULTS

The arrangement and results are listed in Tab.3.

Table 3

Arrangement and results of experiment

No.	Factors						Indexes		
	HAT [°C]	HAV [m.s^{-1}]	SSC [r.min^{-1}]	PIR1 [kW]	PIR2 [kW]	IWC [%]	DR [%/min]	ICP[%]	SEC [kJ/kg.H_2O]
1	1(40)	1(4.00)	1(276)	1(1.0)	1(3.0)	1(20)	0.48	4.48	3406.59
2	1	2(4.10)	2(270)	2(1.5)	2(3.5)	2(18)	0.25	7.32	4473.10
3	1	3(4.95)	3(282)	3(2.0)	3(4.0)	3(22)	0.27	2.51	2938.00
4	1	4(4.66)	4(264)	4(2.5)	4(4.5)	4(24)	1.37	3.45	1793.23
5	1	5(5.30)	5(288)	5(3.0)	5(5.0)	5(28)	1.85	0.93	1365.58
6	2(45)	1	2	3	4	5	2.00	0.63	917.66
7	2	2	3	4	5	1	0.73	3.89	4021.30
8	2	3	4	5	1	2	0.68	11.23	2694.51
9	2	4	5	1	2	3	0.74	0.41	1738.58
10	2	5	1	2	3	4	2.03	5.19	894.32
11	3(50)	1	3	5	2	4	2.15	4.27	984.64
12	3	2	4	1	3	5	2.38	1.45	636.90
13	3	3	5	2	4	1	0.45	6.59	5009.85
14	3	4	1	3	5	2	1.95	16.07	1500.78
15	3	5	2	4	1	3	1.32	3.27	1331.92
16	4(55)	1	4	2	5	3	1.42	2.86	1515.64
17	4	2	5	3	1	4	1.19	4.39	1301.37
18	4	3	1	4	2	5	2.85	1.99	650.17
19	4	4	2	5	3	1	0.57	5.53	4327.77
20	4	5	3	1	4	2	2.43	7.87	1029.87
21	5(60)	1	5	4	3	2	1.05	8.90	2122.63
22	5	2	1	5	4	3	1.62	3.91	1620.35
23	5	3	2	1	5	4	1.46	5.51	1502.18
24	5	4	3	2	1	5	1.96	1.70	647.10
25	5	5	4	3	2	1	0.81	4.81	2406.99

Fig.5 shows the influence of the HAT, HAV, SSC, PIR1, PIR2 and IWC on the DR. The extreme difference analysis shows $R_{IWC}>R_{HAT}>R_{SSC}>R_{HAV}>R_{PIR2}>R_{PIR1}$, where R with the corresponding subscribing represents the extreme different value of each factor. Since the higher the water content of paddy is, the higher the rate of dehydration is and the more the hot air is needed to bring the water out of the drying system, the IWC and HAT become the key factors to the DR. To achieve the maximum DR, HAT=55°C, HAV=5.3m/s, SSC=276 r/min, PIR1=1.0kW, PIR2=4.5kW and IWC=28%.Because the duration of the IR radiation drying process is very short and there is less bound water in the experiment paddy using the conditioning treatment than the actual field paddy, the hot air has more effect in contrast to the infrared radiator.

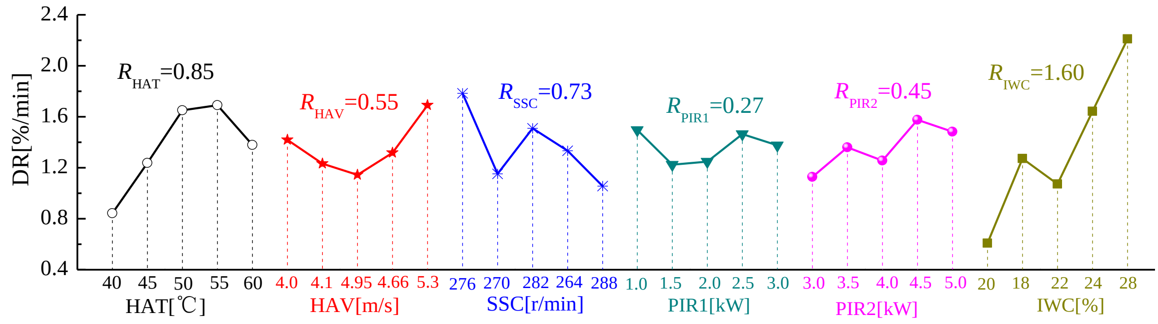

Fig. 5 - Influence of the drying factors on the dehydration rate (DR)

The six factors affecting the ICP in a descending order are: IWC, HAT, SSC, PIR2, PIR1 and HAV according to their extreme difference values. The ICP increases with the rising of DR; hence, the IWC and HAT are also the dominant factors to ICP. The optimal combination of factors can be also obtained as: HAT=40°C, HAV=4.1 m/s, SSC=282 r/min, PIR1=1.0kW, PIR2=3.5kW and IWC=28%.

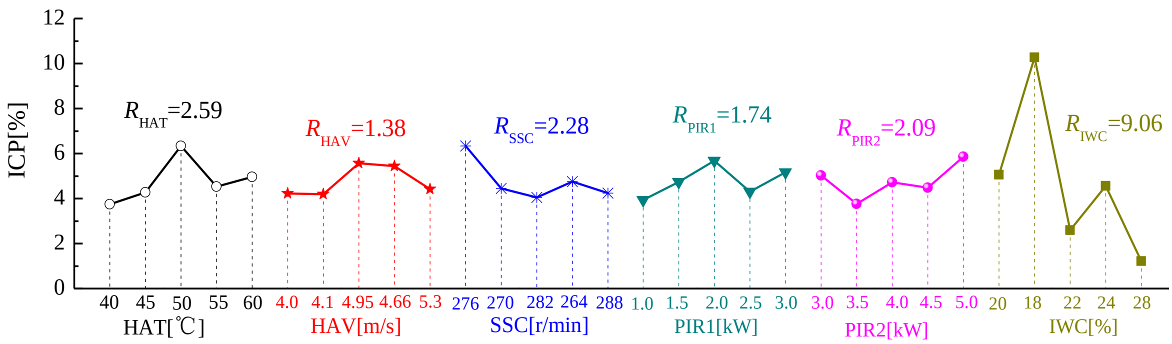

Fig. 6 - Influence of the drying factors on the increased crack percentage

As shown in Fig.7, the influence of the conditions on SEC follows the sequence: IWC, HAV, HAT, SSC, PIR1 and PIR2, and the optimal combination is: HAT=60°C, HAV=5.3 m/s, SSC=276 r/min, PIR1=1.0kW, PIR2=3.0kW and IWC=28%. That is to say, in order to reduce the drying energy consumption, the convection drying should be enhanced while the IR radiator drying should be weakened; meanwhile, the paddy flow should be reduced.

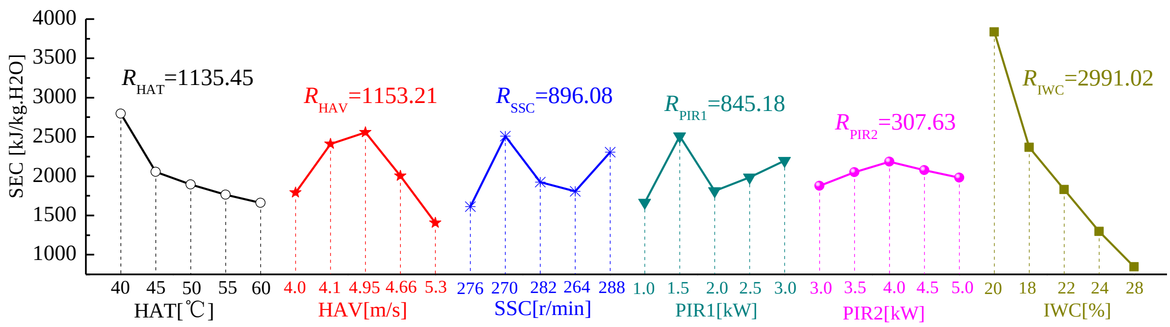

Fig. 7 - Influence of the drying factors on the specific energy consumption

Since the IWC varies with the climate and harvest time and cannot be controlled, the other five factors should be selected according to the DR, ICP and SEC during the actual harvesting process.

CONCLUSIONS

A kind of new paddy drying system was proposed in order to decrease the grain loss due to no timely drying for the high moisture content paddy in the rice main production region of southern China (especially in the double cropping rice region), reduce the handling cost for paddy drying and solve the problem of drying paddy on roadway in our country. Using the electric current generated by the integrated starter/generator(ISG) driven by diesel engine and the exhaust heat of diesel engine as the source of energy, the new drying system equipped with far-infrared and hot air could dry paddy directly in the drying chamber integrated with the screw conveyor and grain collecting tank of the combine harvester. The key problem of multi-field coupling mechanism of paddy flow, hot air and far-infrared was solved through the experimental researches on the effect of paddy flow, hot air and far-infrared radiation on the paddy drying process, and the test results show:

(1)The drying combination of infrared convection embedded in the combine harvester could achieve rapid drying with good drying quality, and the SEC can meet the specification of JB/T10268-2001.

(2)When HAT=55°C, HAV=5.3m/s, SSC=276r/min, PIR1=1.0kW, PIR2=4.5kW and IWC=28%, the highest DR can be achieved; under the case of HAT=40°C, HAV=4.1m/s, SSC=282 r/min, PIR1=1.0kW, PIR2=3.5kW and IWC=28%, the drying quality is the best; in order to acquire the minimum energy consumption, the conditions are: HAT=60°C, HAV=5.3 m/s, SSC=276 r/min, PIR1=1.0kW, PIR2=3.0kW and IWC=28%.

(3)The IWC is the dominant factor to the DR, ICP and SEC, but it cannot be controlled in the actual producing process. The convection drying has more effect on the drying performances compared with the IR radiation drying because of its longer drying duration.

The future work will focus on embedding the whole drying system on the combine harvester and experiment in the actual harvest process.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (grant number31560344) and Science and Technology Project of Jiangxi Province (grant number 20181BBF68016).

REFERENCES

[1] Bai J.W., Luo S.Q., Ye J. et al., (2008), Design of the waste heat utilizing system on multifunctional tractor, *Journal of Agricultural Mechanization Research*, vol. 12, pp. 95-197;

[2] Celma R.A., Rojas S., Lopez-Rodriguez F., (2008), Mathematical modeling of thin- layer infrared drying of wet olive husk, *Chemical Engineering and Processing,* vol. 47, pp.1810-1818;

[3] Chen K.J., Chen Q.C., Zhang Y., (2005), Energy consumption for grain drying in China (中国谷物干燥加工中的能源消耗状况), *Transactions of the CSAE*, vol. 21, pp.173-177;

[4] Dhib R., Broadbent A.D., Thérien N., (1994), Modeling and simulation of the drying of thin sheets in a continuous infrared dryer, *Canadian Journal of Chemical Engineering*, vol. 72, pp. 894-905;

[5] Kuang P., (2016), *Research and development of exhaust heat assisted far IR Rice drying equipment in combine harvester*. (联合收割机中排气余热联合远红外稻谷干燥装置的研发), Dissertation of Jiangxi Agricultural University, pp. 39-46;

[6] Li C.L., (2004), The brief introduction of moisture condition. (米厂谷物加工中水分的调质), *Grain processing*, vol.5, pp.18-19+29;

[7] Liu C.S., Shang T., Yang S.Q., (2017), Analysis on the Influence of the Exchange Area on the Heat Exchange Efficiency during Far-Infrared Convection Combination Grain Drying Process, *ICSGEA: IEEE Computer Society*, pp.117;

[8] Niu X.H., Cao C.W., (1999), Energy saving techniques in grain drying (谷物干燥节能技术), *Transactions of CSAE*, Vol. 6, pp.87-94;

[9] Onwude D.I., Hashim N., Abdan K. et al., (2019), The effectiveness of combined infrared and hot-air drying strategies for sweet potato, *Journal of Food Engineering,* vol. 241, pp.75-87;

[10] Rahmanian- Koushkaki H., Nourmohamadi-Moghadami A., Zare D. et al., (2017), Experimental and theoretical investigation of hot air- infrared thin layer drying of corn in a fixed and vibratory bed dryer, Engineering in Agriculture, *Environment and Food*, vol. 10, pp.191-197;

[11] Sarobol M., Teeta S., Pharanat W. et al., (2018), Numerically simulations of the germinated parboiled thunya-siringlutinous rice under a combined far infrared radiation and air convection drying, *Journal of Physics: Conference Series,* 1144, 012178;

[12] Wang J.H., (2000), Analysis of effecting factors for rice crackle ratio during drying (稻谷干燥爆腰率因素分析), *Cereal & Feed Industry*, vol. 8, pp. 20-21;

[13] Xiang F., Wang L., Yue X.F., (2011), Exergy analysis and experimental study of a vehicle-mounted heat pump–assisted fluidization drying system driven by a diesel generator, *Drying Technology*, vol. 29, pp.1313–1324;

[14] Zare D., Naderi H., Ranjbaran M., (2015), Energy and quality attributes of combined hot-air/infrared drying of paddy*, Drying Technology*, vol. 33, pp. 570-582.