OPTIMIZATION OF REGENERATOR FOR PULSE -TUBE REFRIGERATOR BASED ON RESPONSE SURFACE METHODOLOGIES

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Abstract: In pulse tube refrigerators, the optimization of regenerator is the key to improve the system performance. Taking the regenerator of pulse-tube refrigerator as the research object, based on the single factor simulation, using the regenerator length, regenerator diameter, cold end pressure ratio and working frequency as the influencing factors, taking the cooling efficiency (COP) as the response value, the mathematical model was established by using the central combination Box-Behnken test design, and the response surface analysis was carried out. Through variance analysis (ANOVA) of the regression equation and model diagnosis, it is verified whether the factors have significant impact on the performance of the regenerator. The two-dimensional contour map and three-dimensional surface map of response surface methodology (RSM) were analyzed and the coupling relationship between COP and various factors was innovatively explored. The results show the influence degree of each factor on the refrigeration performance of pulse tube refrigerator. The pairwise coupling among regenerator length, diameter and the cold end pressure ratio (PRES_RATIO) have a significant influence on COP.

Keywords: Pulse-tube Regenerator, REGEN3.3, Response surface method

1. Introduction

Pulse-tube refrigerator is a new refrigerator[1].The temperature gradient is generated by the gas expanding and compressing back and forth in the tube, thus producing low temperature[2]. It has the characteristics of simple structure, high frequency and high reliability, and has a broad development prospect in the field of low temperature.

The regenerator is important to the pulse-tube refrigerator. In recent decades, researchers have carried out a lot of research on optimizing the operating parameters and structural parameters of regenerators. Liu Ying-wen's team introduced convergent and divergent conical regenerator structures to improve the

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performance of the pulse tube refrigerator [3]. S.K. Rout and Huiqin Yu adopted software simulation and experiment methods respectively to optimize the porosity of the regenerator while keeping other parameters unchanged [4-5]. A.Jafarian compared the performance of the regenerator of the pulsed tube refrigerator at low frequency and high frequency[6]. Liu et al. verified the feasibility of activated carbon adsorption of helium gas as regenerative material through experiments [7]. Through thermodynamic analysis, Qiang Cao revealed the working mechanism of applying DC flow when the heat accumulator works with real gas [8]. Z.Hgan experimentally studied the mixtures of helium and nitrogen in a single-stage pulsed tube refrigerator, and the best COP was obtained under the appropriate mixing ratio[9].

According to previous literature, there are many studies on single-objective optimization of COP [10-14], but relatively few studies on multi-parameter optimization of COP. Based on this, REGEN3.3 software was used in this paper to establish the pulse tube regenerator model, and the response surface method was innovatively combined. The regenerator length, regenerator diameter, frequency and cold end pressure ratio were voted as the dependent variables, and the refrigeration coefficient COP was selected as the response value. The influence of coupling of the four parameters on COP is analyzed emphatically, which provides a guiding direction for optimizing the regenerator with multi-parameter coupling. The full name and abbreviation of technical terms are shown in Table 1

Table 1

Full name and abbreviation of technical terms

Full title	abbreviation
variance analysis	ANOVA
response surface methodology	RSM
the cold end pressure ratio	PRES_RATIO
Box-Behnken design	BBD
the cooling efficiency	COP

2. Mathematical model

2.1 Introduction to the regenerator model

In the study, the structure diagram of the pulse tube refrigerator is shown in Fig 1. The pulse tube refrigerator is composed of a linear compressor and a cold unit. The cold unit is composed of hot and cold end heat exchangers, a regenerator, a pulse tube, a phase regulating mechanism.

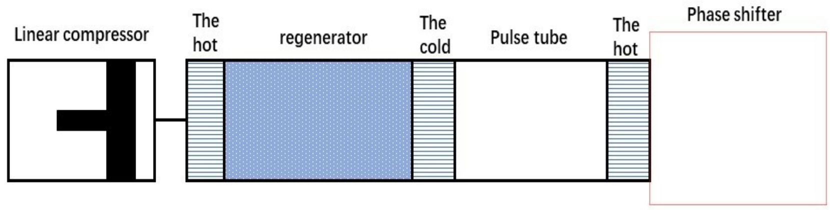


Fig 1 Pulse tube refrigerator structure diagram

REGEN is a software for numerical simulation of regenerators. The software has been updated to REGEN 3.3 version [15-17]. REGEN regards the regenerator as a circular tube filled with porous medium. The working fluid flows through the voids of a porous medium, and exchanges heat with working medium. REGEN is numerically integrated along the one dimensional axis of the regenerator and time t. The designer can input various parameters of the regenerator (structural parameters and operating parameters of the regenerator, etc.) to obtain the simulated output data of REGEN (refrigeration coefficient COP of the regenerator, refrigerating capacity, average pressure drop of the cycle, etc.).

The simulation process of REGEN3.3 is divided into three stages. First, the parameters, including the operation parameters and structure parameters of the regenerator, are input in the program interface of DataGuie. exe. Second, input correction parameters, iteration control parameters and result output control parameters; Third, run DataGui. exe program, get the output data including refrigeration coefficient, cooling capacity, etc., analyze the single effect of the input parameters on the output parameters.

Table 2

Basic input parameters of regenerator

Operating and structural parameters	The Value
Inflation pressure (p_{in}) /MPa	3.4
Temperature of Hot end (t_h) /℃	300
The cold end acoustic power (P_c) /W	3
Temperature of Cold end (t_c) /℃	85
The phase angle of the pressure wave after the mass flow at the cold end (y) /°	20
Number of stainless steel wire mesh (n)	600
Adiabatic expansion coefficient at the ends of hot and cold (a)	0.7
Porosity (p)	0.69

This paper studies the regenerator of pulse tube refrigerator. Using response surface method to conduct coupling analysis of selected parameters, so the numerical value of unselected parameters is determined first. The basic input parameters of the regenerator are shown in Table 2.

2.2 Theoretical basis of pulse refrigerator thermodynamics

Pulse refrigerators [18] are driven by alternating pressure waves emitted by pressure wave generators, causing mass flow and temperature fluctuations, etc. Most parameters in the system change alternately with time, so all oscillating variables can be approximately regarded as sine waves. In all analyses, the higher order harmonics are ignored, and the first order harmonics are retained. The alternating parameters are mainly divided into two categories:

State parameters, such as temperature (t) and pressure (p), can be expressed as：

$$t = t_0 + \delta t = t_0 + t_d \cos(\omega t + \theta_t) \tag{1}$$

$$p = p_0 + \delta p = p_0 + p_d \cos(\omega t + \theta_p) \tag{2}$$

Where, p_0 and t_0 are the mean values of gas temperature and pressure, and t_d and p_d are the amplitude values of fluctuation. $p_d/p_0 < 1$, $t_d/t_0 \leq 1$, therefore, the mean values and approximate values of pressure and temperature can be used to replace the instantaneous values in the analysis.

Under the condition of the steady state, the relevant thermodynamic parameters are expressed by the general time mean, and the gas is an ideal gas by default. Then mass flow ($\dot{m}$) and enthalpy flow ($\dot{h}$) and entropy flow ($\dot{s}$) can be expressed as:

$$\langle \dot{m} \rangle = \frac{1}{\tau}\int_0^\tau \delta\dot{m}dt \frac{1}{\tau}\int_0^\tau |\dot{m}_d| \cos(\omega t + \theta_m)dt = 0 \tag{3}$$

$$\langle \dot{h} \rangle = \frac{1}{\tau}\int_0^\tau \delta\dot{m}\,\delta h dt \tag{4}$$

$$\langle \dot{h} \rangle = \frac{1}{\tau}\int_0^\tau c_p \delta\dot{m}\,\delta t dt = \frac{c_p |\dot{m}_d| t_d \cos(\theta_{mt})}{2} \tag{5}$$

$$\langle \dot{s} \rangle = \frac{1}{\tau}\int_0^\tau \delta\dot{m}\,\delta s dt \tag{6}$$

$$\langle \dot{s} \rangle = \frac{1}{\tau}\int_0^\tau \delta\dot{m}\left(c_p \partial t/t - r_g \partial p/p\right)dt \tag{7}$$

$$\langle \dot{s} \rangle = \frac{1}{2} c_p |\dot{m}_d| \frac{t_d}{t_0}\cos(\theta_{mt}) - \frac{1}{2} r_g |\dot{m}_d| \frac{p_d}{p_0}\cos(\theta_{mp}) \tag{8}$$

Where, $\dot{m}_d$, $\dot{h}_d$, $\dot{s}_d$ are mass flow amplitude, enthalpy flow amplitude and entropy flow amplitude respectively, θ_{mt} is the phase angle of mass flow with temperature, θ_{mp} is the phase angle of temperature and pressure waves, c_p is specific heat capacity at constant pressure, r_g is the gas constant.

There is no empty volume in the ideal regenerator, and the mass flow at each cross section is equal, that is, $|\dot{m}_d|$ is a fixed value. The internal heat transfer of the ideal regenerator is sufficient, and the temperature of the packing and the working medium is the same, that is, T_d is equal to 0. In the ideal regenerator, there is no internal resistance and no pressure drop loss, that is, the amplitude of pressure fluctuation is constant at each section. Therefore:

$$\langle \dot{h} \rangle = 0 \tag{9}$$

$$\langle \dot{s} \rangle = -\frac{1}{2} r_g |\dot{m}_d| \frac{p_d}{p_0} \cos(\theta_{mp}) = \cos\tan t < 0 \tag{10}$$

$$\langle p\dot{v} \rangle_{reg} = \frac{1}{2} t_x r_g |\dot{m}_d| \frac{p_d}{p_0} \cos(\theta_{mp}) \tag{11}$$

Where, $\langle p\dot{v} \rangle_{reg}$ is the internal power of regenerator, t_x is the temperature of each length of the regenerator

3. Response surface optimization

Response surface optimization method [19-20], carries out limited experimental design through reasonable selection of the set of experimental samples, uses multiple quadratic regression equation to fit the functional relationship between various factors and response value, and then analyzes the regression equation, response surface, contour line, etc., to determine the optimal combination. Response surface methodology (RSM) was used to evaluate the influence of some key structural parameters and operating parameters on COP of high frequency pulse regenerator. The specific test process is as presented:

Firstly, the number and range of test parameters are determined according to the influence level and range of each parameter on COP. Secondly, the corresponding RSM Design is carried out on the Design Expert11 software based on the BBD optimization method, and different combinations of parameters are randomly obtained. These combinations are substituted into the REGEN3.3 software to calculate the response value COP. According to the experimental results, the quadratic regression fitting equation is calculated by RSM method. Analysis of variance (ANOVA) was performed on the fitting results. The variance analysis is used to determine whether the regression equation fits well. If the fitting degree is high, the model is considered to be of high reliability, and the result analysis can be carried out. If the fitting degree is poor, the number and range of factors should be adjusted and the design should be re-designed. The quadratic regression model is described by Equation (11)

$$y=\sum_{i=1}^{k}\beta_i X_i+\sum_{i=1}^{k-1}\sum_{j=i+1}^{k}\beta_{ij}X_i X_j+\sum_{j=i+1}^{k}\beta_{ii}X_i^2+\varepsilon+\beta_0 \quad (11)$$

Where: y is the response value of the system; x_i, x_j are random variables; $\beta_0, \beta_i, \beta_{ij}, \beta_{ii}$(i=0, 1, 2, ⋯, k; i=0, 1, 2, ⋯, k) are undetermined coefficients, which are determined by sample iteration; ε is statistical error.

There are many parameters affecting the performance of regenerator in pulse tube refrigerators, including operating parameters (frequency, charging pressure, cold end pressure ratio, etc.) and structural parameters (regenerator length, diameter, packing material and structure). Domestic and foreign researchers have done in-depth research on this aspect. The main parameters affecting the performance of the regenerator were determined by studying the previous literature. In this experiment, the length, diameter, frequency and cold-end pressure ratio of the regenerator were taken as dependent variables. The range and level of each factor were represented by X_1, X_2, X_3 and X_4 according to the experiment, and the response value was the refrigeration performance of the regenerator (COP). Among them, the regenerator length range is 18-24 mm, the regenerator diameter range is 4-6mm, the frequency range is 100-110Hz, and the cold end pressure ratio is 3.4-4.0, as shown in Table 3.

Table 3

Rangs and levels in BBD

factor	Level and code			
	code	-1	0	1
Length of regenerator(A)/mm	X_1	18	20	24
Diameter of regenerator(B)/mm	X_2	4	5	6
Frequency(C)/Hz	X_3	100	105	110
The cold end compression ratio(D)	X_4	3.4	3.7	4.0

4. Results analysis

According to the BBD optimization design of the range and level of each factor, the total number of experiments was randomly obtained for 29 times. The dependent variables of different parameter combinations were input into the REGEN3.3 model, and the regenerator performance COP corresponding to different regenerator lengths, diameters, frequencies and cold-end pressure ratios was calculated. The results are shown in Table 4. In the table, the first column is the test number, the following four columns are the test factors and conditions, and the last column is the test result.

Table 4

Design of experimental matrix

	Factor				COP
	X_1	X_2	X_3	X_4	
1	0.000	1.000	0.000	-1.000	0.1053
2	-1.000	0.000	0.000	1.000	0.106
3	0.000	0.000	0.000	-1.000	0.116
4	0.000	0.000	0.000	0.000	0.1135
5	-1.000	-1.000	0.000	0.000	0.0915
6	1.000	0.000	0.000	-1.000	0.1082
7	0.000	0.000	0.000	0.000	0.1105
8	-1.000	0.000	1.000	0.000	0.1037
9	1.000	0.000	1.000	0.000	0.11
10	0.000	1.000	-1.000	0.000	0.1098
11	0.000	-1.000	1.000	0.000	0.1006
12	-1.000	1.000	0.000	0.000	0.1036
13	-1.000	0.000	-1.000	0.000	0.1065
14	0.000	1.000	1.000	0.000	0.1055
15	1.000	0.000	0.000	1.000	0.1142
16	1.000	0.000	-1.000	0.000	0.114
17	0.000	-1.000	0.000	1.000	0.107
18	0.000	0.000	1.000	1.000	0.1131
19	0.000	1.000	0.000	1.000	0.106
20	1.000	-1.000	0.000	0.000	0.1047
21	0.000	-1.000	0.000	-1.000	0.0938
22	0.000	0.000	0.000	0.000	0.1205
23	1.000	1.000	0.000	0.000	0.1076
24	0.000	0.000	1.000	-1.000	0.1053
25	0.000	-1.000	-1.000	0.000	0.1026
26	0.000	0.000	-1.000	-1.000	0.1078
27	0.000	0.000	-1.000	1.000	0.1153
28	0.000	0.000	0.000	0.000	0.1115
29	-1.000	0.000	0.000	-1.000	0.1028

4.1. ANOVA analysis and model diagnosis

Based on the BBD algorithm, regression analysis is conducted on the data in Table 4 to obtain the quadratic multinomial regression fitting equation of the four factors to COP :

$$\mathrm{COP} = 0.1148 + 0.0037\mathrm{A} + 0.0031\mathrm{B} - 0.0015\mathrm{C} + 0.0027\mathrm{D}$$
$$-0.0023\mathrm{AB} - 0.0003\mathrm{AC} + 0.0007\mathrm{AD} - 0.0006\mathrm{BC} - 0.0031\mathrm{BD}$$
$$+0.0001\mathrm{CD} - 0.0044\mathrm{A}^2 - 0.0088\mathrm{B}^2 - 0.0018\mathrm{C}^2 - 0.0022\mathrm{C}^2$$

Where: A is the length of regenerator, B is the diameter of regenerator, C is the frequency, D is the cold end compression ratio.

In response surface optimization analysis, the accuracy and significance of the quadratic regression equation were tested by analysis of variance. Table 5 shows the ANOVA results of COP response surface optimization model. The sum of squares reflects the overall volatility of the optimized test data, and the variance is obtained by dividing the sum of squares of each part by the degree of freedom. F value reflects the influence of the model on the response value, and P value is used to judge the significance of the corresponding influence of factors. P value less than 0.05 indicates that factors have a great influence on the response. R^2 is an important parameter to judge the validity of the regression equation, and the closer its value is to 1, the higher the accuracy of the model is. The modified fitting coefficient $\mathrm{R}^2_{\mathrm{adj}}$ reflects the percentage change of response value that can be explained by the model. The smaller the difference between the predicted fitting coefficient $\mathrm{R}^2_{\mathrm{adj}}$ and the modified fitting coefficient $\mathrm{R}^2_{\mathrm{Pred}}$, the more consistent they are. The Adeq Precision is used to measure the proportional relationship between effective data and interference. It is generally considered that the value is greater than 4, indicating that the effective data are sufficient, and the model is reliable, and the response value can be accurately predicted. It can be seen from Table 4 that the P value of the model is 0.0002, indicating that the model selected in the test has a very significant impact on the refrigeration coefficient of the regenerator. R^2 value is 0.8908, and $\mathrm{R}^2_{\mathrm{adj}}$ value is 0.7816, indicating that the predicted value of the model is in good agreement with the actual value. The P values of regenerator diameter, length, cold pressure ratio and BD , A^2 , B^2 are all less than 0.05, indicating that the parameters have a major influence on the output power, while the P-values of other parameters, such as C, are greater than 0.05, indicating that the influence is small. Since the F value of length, diameter, cold-end pressure ratio and frequency are 19.53, 13.88, 10.97 and 3.11 respectively, the order of influence degree is the length>the diameter>the cold end compression ratio> the frequency. The coefficient of variation (CV) is 2.71%, less than 10%, which indicates that the reliability of the test and the accuracy of the model are high. The Adeq Precision is 10.9164, greater than 4, which indicates that the adopted signal is suitable and can be used within the space range confirmed by the model.

Table 5

ANOVA for thermal efficiency

Source	Sum of square	df	Mean Square	F-value	P-value	
Model	0.0010	14	0.0001	8.16	0.0002	significant
A-length	0.0002	1	0.0002	19.53	0.0006	
B-diameter	0.0001	1	0.0001	13.88	0.0023	
C-frequent	0.0000	1	0.0000	3.11	0.0996	
D-PRES_RATIO	0.0001	1	0.0001	10.97	0.0051	
AB	0.0000	1	0.0000	2.49	0.1366	
AC	3.60E-07	1	3.60E-07	0.0424	0.8398	
AD	1.960E-06	1	1.960E-06	0.2310	0.6382	
BC	1.322E-06	1	1.322E-06	0.1558	0.6990	
BD	0.0000	1	0.0000	4.60	0.0499	
CD	2.250E-08	1	2.250E-08	0.0027	0.9597	
A2	0.0001	1	0.0001	14.46	0.0019	
B2	0.0005	1	0.0005	56.60	＜0.0001	
C2	0.0000	1	0.0000	2.30	0.1520	
D2	0.0000	1	0.0000	3.40	0.0866	
Residual	0.0001	14	8.486E-06			
Lack of Fit	0.0001	11	5.2550E-06	0.2585	0.9589	Not significant
Pure Error	0.0001	3	0.0000			
Cor Total	0.0011	28				

Fig 2 shows the relationship between COP and REGEN model values for refrigeration performance predicted by the response surface (RSM).See from the Fig 2, most design points are very close to the figure of diagonal lines, the simulation results show that the model can effectively predict the thermodynamic properties of pulse tube refrigerator.

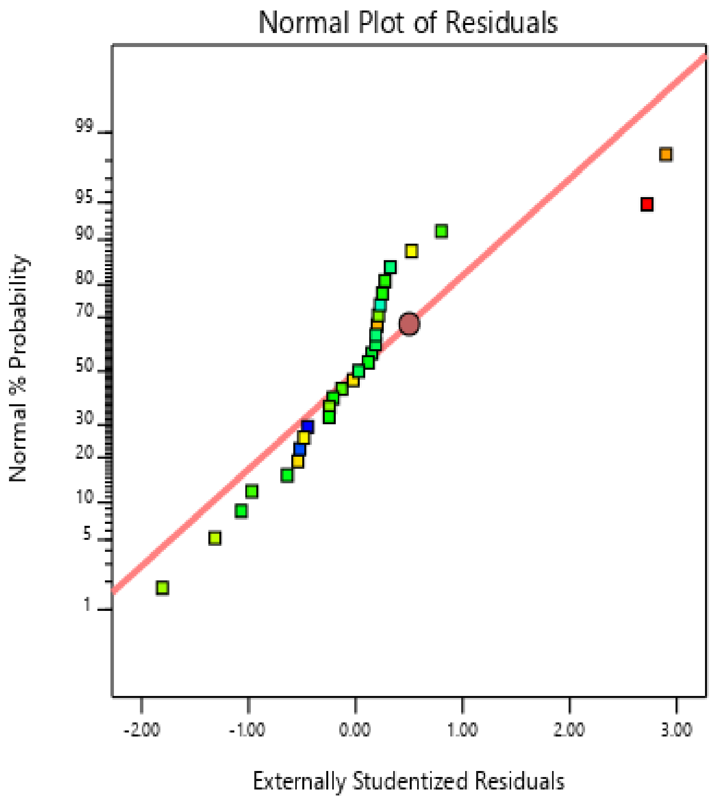


Fig 2 RSM predictions versus REGEN model's results

4.2 Coupling analysis among factors

In order to study the four parameters' effect on the performance of pulse tube refrigerator, the RSM analysis method provides multi-factor two-dimensional contour plot and three-dimensional surface analysis, showing the interaction of the two factors on the COP. Figures 3-8 respectively show the interaction of AB, AC, AD, BC, BD and CD on COP.

Fig 3 shows the combined effect of the length and diameter of the regenerator on COP, where the frequency is 105 Hz and the PRES_RATIO is 1.28. According to Fig 3 (a), when the diameter of the regenerator is increased to 22 mm and 5.2 mm, COP reaches the maximum value. See from Fig 3 (b), the interaction between the length of regenerator and that the diameter of regenerator has a significant influence on COP, and there is a nonlinear relationship between COP and the diameter and length of regenerator. COP increases with the increase of diameter and length then decreases, which may be because the increase of length leads to the increase of flow resistance loss. It is necessary to select the appropriate length and diameter to optimize the regenerator.

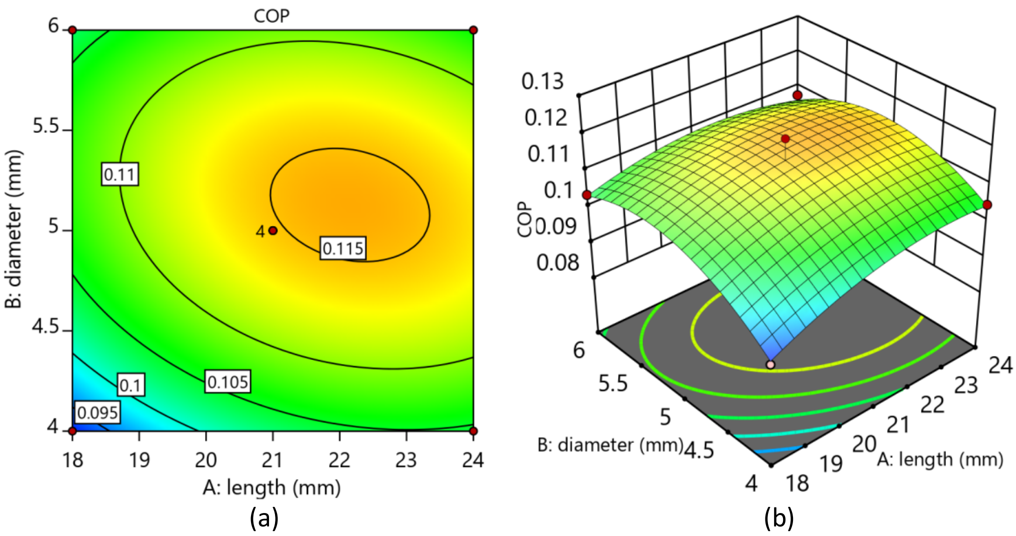


Fig 3 Combined effects of length and diameter on COP

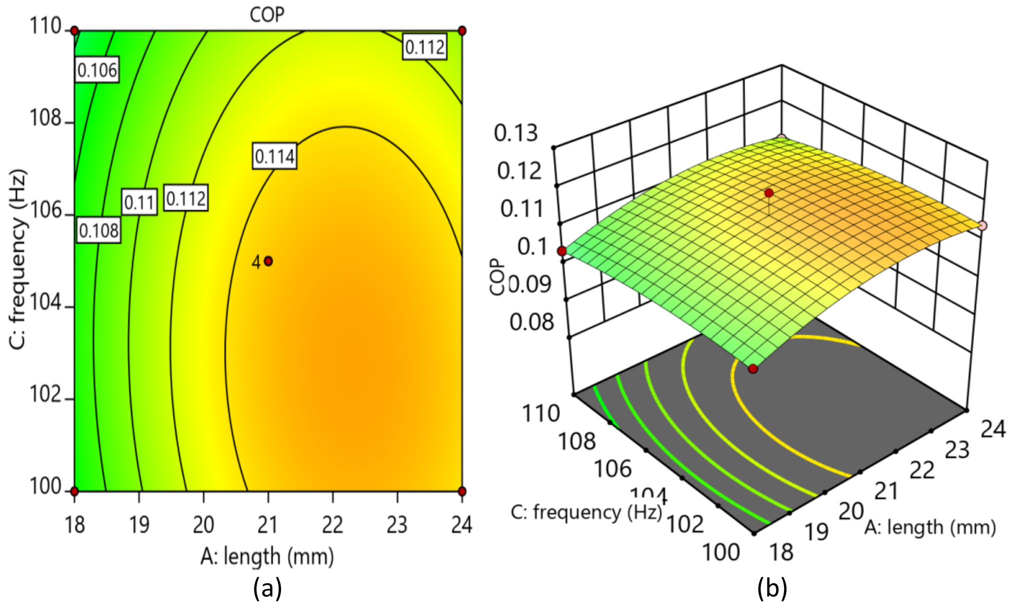
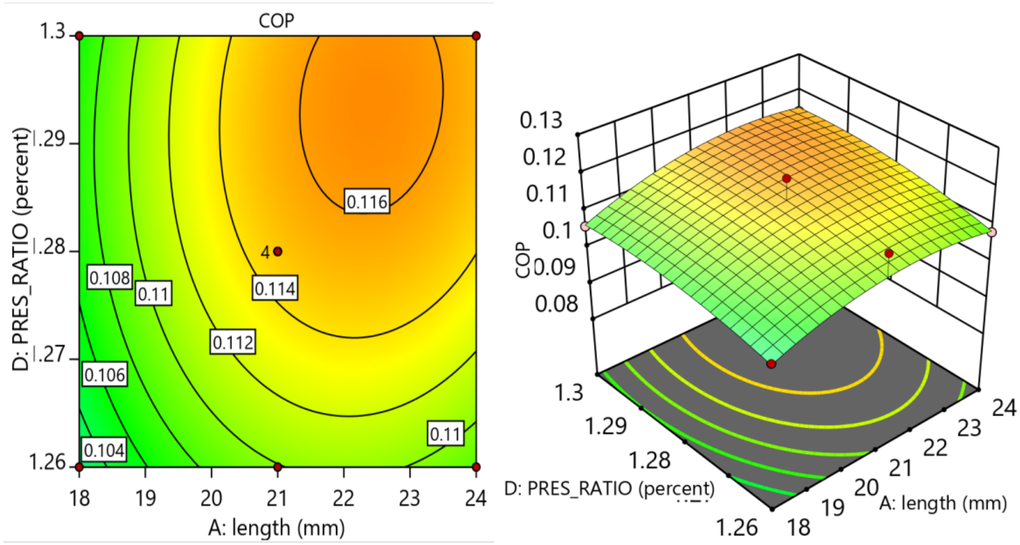


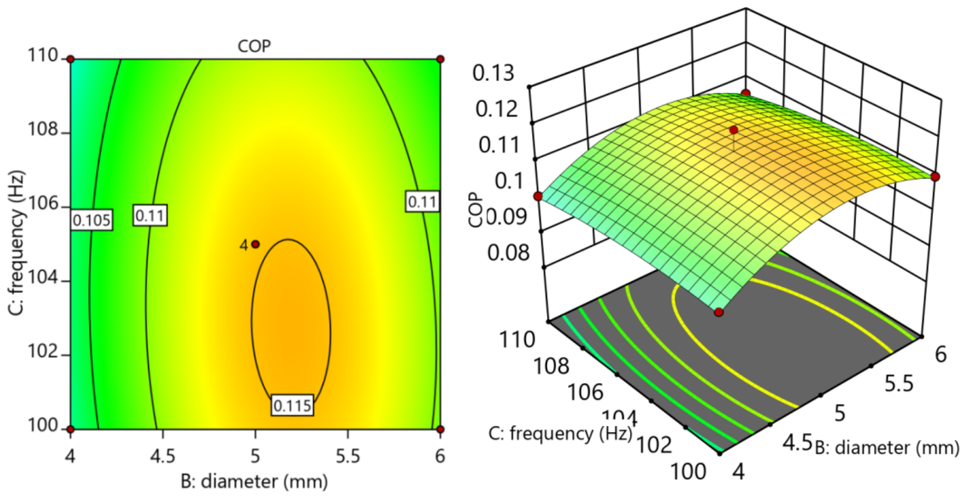
Fig 4 Combined effects of length and frequency on COP

Fig 4 shows the comprehensive effect of regenerator length and frequency on COP. In this case, the diameter is 5 mm and the PRES_RATIO is 1.28. According to Fig 4 (a), when the diameter of the regenerator increases to 22 mm and the frequency reaches 105, COP reaches the maximum value. As can be seen from Fig 4 (b), COP is linearly related to the length when the length is within the range of 18-22 mm. However, the length of the regenerator has little influence on COP when the length exceeds this range. There is some interaction between frequency and COP, but it is not significant.



(a) (b)

Fig 5 Combined effects of length and PRES-RATIO on COP



(a) (b)

Fig 6 Combined effects of diameter and frequency on COP

Fig 5 displays the comprehensive effect of the regenerator length and the cold end pressure ratio on COP. At this time, the diameter is 5 mm and the length is 105 mm. According to Fig 5 (a), when the regenerator length increases to 22.5 mm and the PRES_RATIO is 1.295, COP reaches the maximum value. By fig 5 (b), the COP in the PRES_RATIO and the length increases first then decreases. The causes of this phenomenon: within a certain length, the heat transfer loss and pressure drop loss increase. But with the continuous increase of the length, the heat transfer loss decreases, and the increase of the pressure drop loss will be greater than the decrease of the heat transfer loss.

Fig 6 displays the effect of the combined effect of frequency and diameter on COP. In this case, the regenerator length is 21 mm and the PRES_RATIO is 1.28. As shown in Fig 6 (a) and (b), the interaction between diameter and frequency has an influence on COP, and the influence of diameter on COP is dominant. Fig 7 shows the effect of the combined effect of the PRES_RATIO and diameter on COP. In this case, the regenerator length is 21 mm and the frequency is 1.28. As shown in Table 4, the combined P value of the PRES_RATIO and diameter is less than 0.05, so the diameter of the regenerator and the PRES_RATIO have significant influence on COP.

As shown in Fig 7, when the PRES_RATIO and diameter are the minimum, COP displays a minimum value. There is a linear relationship between the cold end pressure ratio and COP. COP increases with the increase of the PRES_RATIO, and COP increases first and then decreases under the interaction of the two. When the diameter is 5 mm and the pressure ratio is 1.29, COP reaches the maximum.

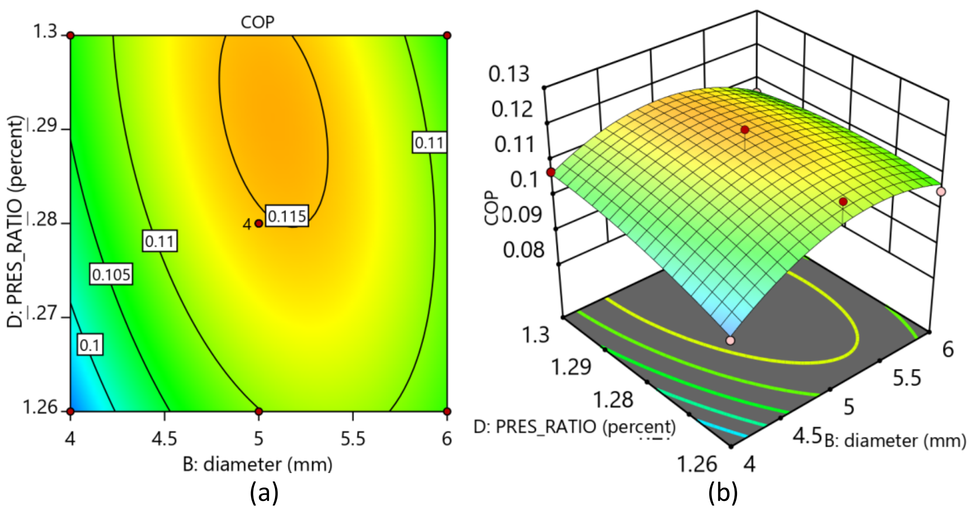


Fig 7 Combined effects of diameter and PRES-RATIO on COP

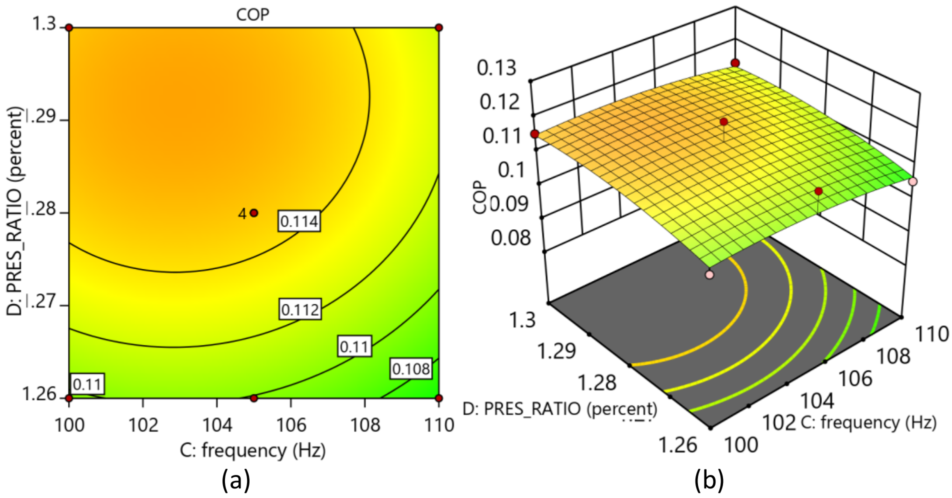


Fig 8 Combined effects of frequency and PRES-RATIO on COP

Fig 8 shows the effect of the combined effect of the PRES_RATIO and frequency on COP. In this case, the length is 21 mm and the diameter is 5 mm. As shown in Fig 8 (a) and (b), there is a positive correlation between COP and the PRES_RATIO and a negative correlation with frequency. This is because the pressure drop loss of the regenerator increases as the frequency increases. When the frequency is 100 Hz and the PRES_RATIO is 1.3, COP reaches its maximum value.

5. Conclusion

Based on BBD method, 29 test matrices were arranged to establish the quadratic regression model of COP. Through variance analysis of regression equation and model diagnosis, it is found that the selected parameters (length, diameter, cold end pressure ratio) have significant effect on the performance of pulse tube regenerator. The response surface prediction model is consistent with the calculated results of REGEN3.3, which proves the effectiveness and reliability of the model.

The influence of various factors on the refrigeration performance of the pulsed tube refrigerator is the length, diameter, cold end pressure ratio, frequency.

Based on the two-dimensional contour map and three-dimensional surface map of RSM, the influence law of the interaction between the two factors on COP is proved. The results show that with the increase of length and diameter, the COP first increases and then decreases, COP increases with the increase of the PRES_RATIO. Frequency has little effect on COP and presents a negative growth trend. The pairwise coupling among regenerator length, diameter and cold end pressure ratio has a significant influence on COP. In the future optimization of pulse tube regenerator, these three parameters need to be reasonably selected, and the design of high frequency regenerator is also the key optimization target in the future. This article has a good guiding significance to optimize the regenerator of pulse tube refrigerator

REFERENCES

[1] *J.R. Olson, G.W. Swift,* Acoustic streaming in pulse tube refrigerators: tapered pulse tubes, Cryogenics, Volume 37, Issue 12, 1997.

[2] *D.L. Gardner, G.W. Swift,* Use of inertance in orifice pulse tube refrigerators, Cryogenics, Volume 37, Issue 2, 1997.

[3] *Y Liu, Y He,* A new tapered regenerator used for pulse tube refrigerator and its optimization, Cryogenics, Volume 48, Issues 11–12,2008.

[4] *S.K. Rout, A.K. Gupta, B.K. Choudhury, R.K. Sahoo, S.K. Sarangi,* Influence of Porosity on the Performance of a Pulse Tube Refrigerator: A CFD Study, Procedia Engineering, Volume 51,2013.

[5] *H Yu, Y Wu, L Ding, Z Jiang, S Liu,* An efficient miniature 120 Hz pulse tube cryocooler using high porosity regenerator material, Cryogenics, Volume 88, 2017.

[6] *A. Jafarian, F. Roshanghalb, M.H. Saidi, F. Imanimehr,* Comparative investigation of low and high frequency pulse tube regenerators, Scientia Iranica, Volume 18, Issue 2,2011.

[7] *L Chen, C Kong, X Wu, Y Zhou, J Wang,* Specific heat capacities and flow resistance of an activated carbon with adsorbed helium as a regenerator material in refrigerators, New Carbon Materials, Volume 33, Issue 1,2018,

[8] *Q Cao, Z Sun, Z Li, M Luan, X Tang, P Li, Z Jiang, L Wei,* Reduction of real gas losses with a DC flow in the regenerator of the refrigeration cycle, Applied Energy, Volume 235, 2019

[9] *Z.H Gan, G.B Chen, G Thummes, C Heiden,* Experimental study on pulse tube refrigeration with helium and nitrogen mixtures, Cryogenics, Volume 40, Issues 4-5,2000.

[10] *J Du, R N Li , X Wu , et al,* Study on Optimization Simulation of Scr Denitration System for Marine Diesel Engine. Polish Maritime Research, 2018, 25(s3):13-21.

[11] *J.M. Belman-Flores, J.M. Barroso-Maldonado, A.P. Rodríguez-Muñoz, G. Camacho-Vázquez,* Enhancements in domestic refrigeration, approaching a sustainable refrigerator-A review, Renewable and Sustainable Energy Reviews, Volume 51, 2015.

[12] *J.Du, R Li,H Wang, X Wu,* Environmental Study on Supercritical CO2 Extraction of Nanocrys talline. Ekoloji, 107(28): 3169-3175.2019

[13] *J Du, Zhao H, Xue Y,* Flow Field Simulation and Experimental Analysis of Flue Guide Plate o f Marine Desulfurization Tower. Journal of Coastal Research, 2020, 115(sp1):396.

[14] *Gary J, O' Gallagher A, Radebaugh R, et al.* REGEN 3.3: User Manual. America: NIST, 2008.

[15] *L Luo, X Chen, Y Xia,* Optimization of 45K Stirling Refrigerator with Layered Structure Based on Regen3.3. Vacuum and low temperature, 2015, 21(04):226-229.

[16] *Y Huang, Z H Jiang, X Chen,* Optimization Design and Experiment of Stirling Refrigerator Layer Regenerator. Cryogenic Engineering, 2014(02):14-18.

[17] *L Fang,* Comparative Simulation Study on Performance of Recyclative Cryogenic Refrigerator Using Helium-3 and Helium-4 as Working Fluid. Shanghai Jiao Tong University,2012

[18] *P C Jin, L Wu,* Box-Behnken response surface methodology for optimization of the effects of processing and processing integration process on polysaccharides from Polygonatum yunnanensis. Modern Chinese Traditional Medicine: 1-9[2021-04-29].

[19] *S Liu, Y Zhou, P Lin,* Box-Behnken response surface methodology for the optimization of alcohol extraction process of Zihong Shengji ointment. Journal of Hunan University of Chinese Medicine, 2021,41(04):528-535.
[20] *J Du, R Li, X Wu, et al,* Modelling and Optimisation of Vacuum Collection System for Cruise Ship Kitchen Garbage. Polish Maritime Research, 2020, 27(1):152-161.