SENSITIVITY ANALYSIS OF THERMOACOUSTIC OSCILLATION IN CRYOGENICS SYSTEM BASED ON RESPONSE SURFACE METHOD

by

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In the practical application of cryogenic systems, the presence of thermoacoustic oscillation can cause a series of adverse consequences such as pressure fluctuations, thermal leakage, structural damage, and so on. To ensure stable operation of the system, variable cross-section control pipe fittings are introduced, and response surface analysis method is used to optimize the parameter design of the control pipe fittings. A series of simulations have been conducted and the response surface method is introduced to conduct variance analysis on the simulation results, and obtain the regression model of the system pressure ratio, then analyze the interaction between parameters. The analysis of variance shows that the correlation coefficient and adjustment coefficient are both close to 1.0, the signal to noise ratio is high, and the fitting degree of the regression model is good. The prediction error of the regression model for the pressure ratio is within ±10, and the distribution of the residual meets the random normal distribution, which can predict the system performance within the parameter design range. The interaction between pipe diameter and length has no significant impact on the oscillation state, so in design, priority should be given to the impact of location and pipe diameter. This work will provide the basis for determining the optimal control structure size of oscillation-free piping system.

Key words: *thermoacoustic oscillation, sensitivity analysis, response surface method, cryogenics*

Introduction

In the practical application of cryogenic systems, ensuring the control accuracy of parameters such as temperature, liquid level, and pressure in a cryogenic system is the key to achieving system stability. Large amplitude pressure oscillations are the main characteristics of instability. Therefore, to ensure stable system operation, it is necessary to take effective suppression strategies to reduce thermoacoustic oscillation (TAO) to an acceptable level. The TAO is self-excited pressure oscillation that reflects instability. Since the development of

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liquid rocket engines in the 1930's, the adverse consequences of TAO have become apparent, including thrust oscillations, structural damage, increased heat transfer, and component or payload failures. Although decades of research have been conducted in Germany, the USA, the Soviet Union [1, 2], and recently in the gas turbine industry since the 1930's, TAO is still a serious problem. The TAO found in the operation of the low temperature helium distribution system of the Taiwan Photon Source Superconducting Radio Frequency [3, 4] and the main low temperature system of the superconducting linear accelerator [5] can lead to pressure fluctuations and additional energy dissipation. In addition, TAO observed in a refrigerant free cryostat for temperature measurement with a single pressure refractive index gas [6, 7] results in a huge heat flux from the hot end to the cold end [8], and has a significant impact on control accuracy. Therefore, it is necessary to study the characteristics of TAO in order to control the conditions under which they occur or can be eliminated.

To avoid these undesirable pressure oscillations, a gas buffer is connected to the exhaust pipeline of the helium treatment pipeline in practical engineering to suppress the TAO phenomenon without modifying the exhaust pipeline [9]. In addition, an acoustic resonator is connected to the hot end through a throttle valve, orifice, or multi hole plug and serves as a dynamic damper [10]. However, such resistance devices will lead to complex flow separation or vortex pair phenomena, which make the flow pattern of the system more complex. The introduction of jet pumps [11] and phase regulators can improve the thermoacoustic conversion efficiency without complicating the system. The heat loss can be decreased from 30 W to 6.5 W by reversing the orientation of the jet pump, when the input heat power supplied to the prime mover is 100 W [12]. The simulated jet pump performance [13] is compared to an existing quasi-steady approximation which is shown to only be valid for small displacement amplitudes compared to the jet pump length. In addition, a phase adjuster (PA) [14, 15] is introduced by narrowing the cross-sectional area to improve the efficiency of the engine, and the efficiency of heat-to-sound energy conversion in the loop-tube-type thermoacoustic prime mover is increased by adjusting the inner diameter of PA [16, 17]. Inspired by the previous structure, we applied a pipe insert with a sudden contraction or expansion structure to achieve oscillation-free in a cryogenic system, and numerically studied the impact of the position and radius of the pipe insert on system oscillation [18]. The TAO phenomenon can be successfully suppressed by our structure without changing the overall structure of the exhaust pipe.

However, for the optimization design of the structure, it is necessary to consider the synergistic relationship of various aspects, which involves the multi-objective optimization of the structural parameters of the mutation section. In previous studies, single factor analysis is often used to optimize the system or components, that is, to conduct independent research on each factor affecting the system or components, find the best value of the factor on the premise of ensuring the other parameters remain unchanged, and then carry out separate optimization research on other factors in turn. This traditional optimization method is not only time-consuming and inefficient, but also ignores the interaction between parameters. As a result, the final parameter combination may not be the optimal combination of the system, especially for the system parameter optimization problem with strong interaction between parameters. For a practical thermal system, there are often complex problems of interaction and highly matching relationship between various parameters and the change of one parameter may cause other parameters to deviate from the optimal range. Therefore, in the process of optimization design, it is necessary to consider the interaction between parameters. To realize the sensitivity analysis of pipe fitting structural parameters and system performance, this paper proposes a modelling method, namely response surface methodology (RSM) [19, 20].

In this paper, the pipe fitting with the structure of sudden shrinkage or expansion is adopted to realize the free-oscillation operation of the low temperature system. The influence of the installation position, radius and length of the pipe fitting in the low temperature transport pipe on the oscillation state of the system is studied numerically. Next, the influences of pipe fitting position and structure size on oscillation characteristics are investigated by RSM. Finally, the optimized parameters of pipe fitting position and structure size are obtained to control the oscillation characteristics of the cryogenic system.

Model and method

Model

A typical cryogenic tube system with length L = 1 m and internal diameter d_0 = 5.7 mm is shown in fig. 1(a). The contraction and expansion structures are shown in fig. 1(c) and fig. 1 (d), respectively. The dotted box indicates the location of the piping insert. The main

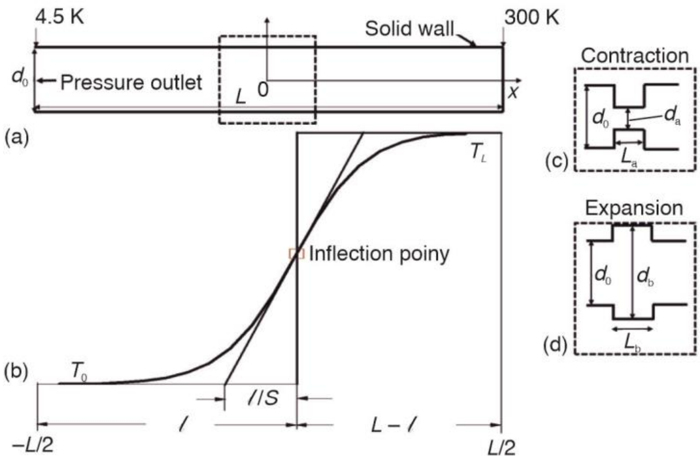

Figure 1. (a) A typical tube model for the cryogenic system, (b) the mean temperature distribution function along the tube, (c) a piping inserts with an abrupt contraction, and (d) a piping inserts with an expansion structure

size and position parameters of the structures are shown in tab. 1. The L_a and L_b are the length for the contraction and expansion, are both kept at 50 mm in study. As demonstrated in fig. 1(b), the average temperatures in the cold and warm parts are T_L = 300 K and T_0 = 4.5 K, respectively, which create a non-linear temperature gradient across the piping system. The jumping point x_0 in the piecewise constant temperature distribution of the tube is the inflection point. The form of the *S*-shaped connection function is a tangential function, and the temperature distribution $T_e(x)$ is given [21]:

$$\frac{T_e(x)}{T_L} = \frac{G(x)-G(0)}{1-G(0)} + \frac{1}{\alpha}\left[\frac{1-G(x)}{1-G(0)}\right] \tag{1}$$

with

$$G(x) = \frac{g(x)+g(2L-x)-1}{2g(L)-1} \tag{2}$$

and

$$g(x)=\frac{1}{2}\tanh[S_g(x-x_0)]-\frac{1}{2}\tanh[S_g(x+x_0)]+1 \tag{3}$$

where $\alpha = T_L/T_0$ represents the temperature ratio with $T_0 = T_e(0)$ and the steepness, S, is determined:

$$S_g=\frac{2l}{T_L-T_0}\left(\frac{\mathrm{d}T_e}{\mathrm{d}x}\right)_{x=l} \tag{4}$$

To illustrate the position of the inflection point, the ratio ε of the cold end tube length, l, to the warm end tube length, $(L - l)$, is defined:

$$\varepsilon = l / L \tag{5}$$

Table 1. The main size and position parameters of the structure

Diameter ratio	Position [m]								
0.18	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
0.35	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
0.52	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
0.7	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
0.88	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
1.23	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
1.4	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
1.75	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
2.11	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
2.46	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
2.81	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
3.16	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4
3.51	–0.4	–0.3	–0.2	–0.1	0	0.1	0.2	0.3	0.4

Method

The RSM integrates statistical and mathematical processing methods, and can determine the relationship between design parameters and response indicators according to relevant criteria, and obtain the mutual influence relationship between design parameters and response:

$$y = f(x_1, x_2, x_3, \ldots, x_{kk}) + \delta \tag{6}$$

where y represents the response to target, $x_1,x_2,\cdots,x_{\mathrm{kk}}$ represent the independent variables, the subscript kk denotes the number of variables, and δ is the statistical error.

To evaluate the effect of structural parameters on the oscillation characteristics of cryogenic systems, RSM can be used to establish a multi-parameter nonlinear function between the operating parameters and the pressure amplitude. In general, the second-order model is:

$$y=\beta_0+\sum_{i=1}^{kk}\beta_i x_i+\sum_{i=1}^{kk-1}\sum_{j=2}^{kk}\beta_{ij}x_i x_j+\sum_{i=1}^{kk}\beta_{ii}x_i^2+\delta \tag{7}$$

where $\beta_0, \beta_i, \beta_{ij}$, and β_{ii} ($i = 0, 1, 2, \cdots, kk$; $j = 0, 1, 2, \cdots, kk$) represent regression coefficients for intercept, linear, interaction and quadratic terms, respectively, x_i and x_j represent the independent variables.

The RSM is used to study the evaluation procedure of the effect of structural operating parameters on the oscillation characteristics of cryogenic systems. The first step is to select the independent variables and target parameters. According to the structural parameters, the effective domains of three factors are also determined, with –1, 0, and 1 representing the minimum, intermediate and maximum values of the parameters, respectively. In the second step, Box-Behnken Design (BBD) of RSM is used to design and generate the experimental matrix, as shown in tab. 2. Based on the low temperature thermoacoustic system, the effective range of three factors is determined. The table lists the corresponding operating variables and their levels in BBD. The data of three structural parameters (A, B, and C) are calculated by simulation.

Table 2. Range and level of independent variables

Factors	Level		
	−1	0	1
A : position [m]	–0.4	0	0.4
B : length [mm]	50	100	120
C : r/r_0	0.18	1.75	3.51

The third step is the design matrix based on BBD. The corresponding oscillatory response is obtained by simulation. The experimental results of the response are shown in tab. 3. The first column of the table shows the number of runs, the second to the fourth columns represent different combinations of structural parameters, and the last column shows the response to the design conditions. The fourth step is to analyze the experimental results and formulate the equations as functions of the operating parameters. Analysis of variance (ANOVA) is used to analyze the relationship between the operating parameters and the system oscillation pressure, and to determine the parameter combination that plays a key role in the oscillation result. In ANOVA analysis, R^2 is usually used to test the quality of the fit, and the closer a value is to 1, the higher the functional relationship is, the better the fitted model. If this value is skewed, increase the number of experimental designs and repeat steps 2-4 until a more satisfactory fit is obtained. In the last step, the fitting function between the oscillatory pressure ratio and the operating parameters obtained in the fourth step can be used to conduct sensitivity analysis on the operating parameters, study the influence of different operating parameters and their combinations on the oscillation state changes, and then predict and analyze the oscillation results to optimize the combination of operating parameters.

Results and discussion

Analysis of variance

Analysis of Variance is mainly used to test the significant difference between the means of two or more samples. The variance that deviates from the total mean is called the total variance, and the ratio of the total variance to the degrees of freedom of the model is the average variance. The F value is equal to the ratio of the average variance of the item to the average variance of the error, which is used to evaluate the impact of the parameter on the response value. Generally, when the probability in ANOVA is less than 0.05, it is considered that this parameter item has a significant impact on the response value, and the design of this parameter should be given priority. The accuracy of model fitting is judged by correlation coefficient and adjustment coefficient. When the correlation value is close to 1.0, it indicates that the model has high accuracy and can predict the response value within the design range.

Table 3. Experimental design table

Order	Design parameters			Response values	Order	Design parameters			Response values
	A position [m]	B length [mm]	C r/r_0	Pressure ratio		A position [m]	B length [mm]	C r/r_0	Pressure ratio
1	–0.40	50	3.51	1.00	74	0.20	50	0.70	1.00
2	–0.30	50	3.51	1.00	75	0.30	50	0.70	1.00
3	–0.20	50	3.51	1.00	76	0.40	50	0.70	1.00
4	–0.10	50	3.51	1.00	77	0.00	50	0.70	1.03
5	0.1	50	3.51	1.42	78	–0.40	50	0.53	1.00
6	0.30	50	3.51	1.92	79	–0.30	50	0.53	1.00
7	0.40	50	3.51	2.08	80	–0.20	50	0.53	1.00
8	0.00	50	3.51	1.00	81	–0.10	50	0.53	1.00
9	–0.40	50	3.16	1.00	82	0.10	50	0.53	1.00
10	–0.30	50	3.16	1.00	83	0.20	50	0.53	1.00
11	–0.20	50	3.16	1.00	84	0.30	50	0.53	1.00
12	–0.10	50	3.16	1.00	85	0.40	50	0.53	1.00
13	0.10	50	3.16	1.19	86	–0.40	50	0.35	1.00
14	0.40	50	3.16	1.80	87	–0.30	50	0.35	1.00
15	0.00	50	3.16	1.00	88	–0.20	50	0.35	1.00
16	–0.40	50	2.81	1.00	89	–0.10	50	0.35	1.00
17	–0.30	50	2.81	1.00	90	0.10	50	0.35	1.00
18	–0.20	50	2.81	1.00	91	0.20	50	0.35	1.00
19	–0.10	50	2.81	1.00	92	0.30	50	0.35	1.00
20	0.10	50	2.81	1.29	93	0.40	50	0.35	1.00
21	0.40	50	2.81	1.91	94	0.00	50	0.35	1.00
22	0.00	50	2.81	1.00	95	–0.40	50	0.18	1.00
23	–0.40	50	2.46	1.00	96	–0.30	50	0.18	1.00
24	–0.30	50	2.46	1.00	97	–0.20	50	0.18	1.00
25	–0.20	50	2.46	1.00	98	–0.10	50	0.18	1.00
26	–0.10	50	2.46	1.00	99	0.10	50	0.18	1.00
27	0.10	50	2.46	1.23	100	0.20	50	0.18	1.00
28	0.00	50	2.46	1.00	101	0.30	50	0.18	1.00
29	–0.40	50	2.11	1.00	102	0.40	50	0.18	1.00
30	–0.30	50	2.11	1.00	103	0.00	50	0.18	1.00
31	–0.20	50	2.11	1.00	104	–0.40	100	3.16	1.24
32	–0.10	50	2.11	1.00	105	–0.40	60	3.16	1.30
33	0.10	50	2.11	1.24	106	–0.40	120	1.75	1.04
34	0.40	50	2.11	1.61	107	–0.30	60	0.35	1.01
35	0.00	50	2.11	1.00	108	–0.40	60	0.35	1.00
36	–0.40	50	1.75	1.00	109	–0.30	60	3.16	1.22
37	–0.30	50	1.75	1.00	110	–0.40	120	3.16	1.05
38	–0.20	50	1.75	1.00	111	–0.30	100	3.16	1.04
39	–0.10	50	1.75	1.00	112	–0.30	120	3.16	1.18
40	0.10	50	1.75	1.18	113	–0.20	60	0.35	1.01
41	0.20	50	1.75	1.19	114	–0.20	60	3.16	1.19
42	0.30	50	1.75	1.27	115	–0.20	100	3.16	1.17
43	0.40	50	1.75	1.28	116	–0.20	120	3.16	1.14
44	0.00	50	1.75	1.00	117	–0.10	60	0.35	1.02
45	–0.40	50	1.40	1.00	118	–0.10	60	1.75	1.21
46	–0.30	50	1.40	1.00	119	–0.10	100	0.35	1.03
47	–0.20	50	1.40	1.00	120	–0.10	100	1.75	1.22

→

Table 3. Continuation

48	–0.10	50	1.40	1.00	121	–0.10	100	3.16	1.04
49	0.10	50	1.40	1.03	122	–0.10	120	0.35	1.03
50	0.20	50	1.40	1.00	123	–0.10	120	1.75	1.28
51	0.30	50	1.40	1.01	124	0.00	60	0.35	1.30
52	0.00	50	1.40	1.00	125	0.00	100	0.35	1.31
53	–0.40	50	1.23	1.00	126	0.00	100	1.75	1.36
54	–0.30	50	1.23	1.00	127	0.00	100	3.16	1.25
55	–0.20	50	1.23	1.00	128	0.00	120	0.35	1.29
56	–0.10	50	1.23	1.00	129	0.00	120	3.16	1.00
57	0.10	50	1.23	1.00	130	0.10	100	0.35	1.54
58	0.20	50	1.23	1.00	131	0.10	100	1.75	1.59
59	0.30	50	1.23	1.00	132	0.10	100	3.16	1.34
60	0.40	50	1.23	1.00	133	0.10	120	0.35	1.51
61	0.00	50	1.23	1.00	134	0.20	100	1.75	1.73
62	–0.40	50	0.88	1.00	135	0.20	100	3.16	1.49
63	–0.30	50	0.88	1.00	136	0.30	100	0.35	1.86
64	–0.20	50	0.88	1.00	137	0.30	100	1.75	1.77
65	–0.10	50	0.88	1.00	138	0.30	100	3.16	1.58
66	0.10	50	0.88	1.00	139	0.30	120	0.35	1.85
67	0.20	50	0.88	1.00	140	0.30	120	1.75	1.84
68	0.30	50	0.88	1.00	141	0.40	100	0.35	1.89
69	0.40	50	0.88	1.00	142	0.40	100	1.75	1.96
70	0.00	50	0.88	1.01	143	0.40	100	3.16	1.82
71	–0.40	50	0.70	1.00	144	0.40	120	0.35	1.89
72	–0.30	50	0.70	1.00	145	0.40	120	1.75	1.75
73	–0.20	50	0.70	1.00	146	0.10	50	0.70	1.00

The ANOVA of the system pressure ratio is shown in tab. 4. As can be seen from the table, the correlation coefficient and adjustment coefficient are 0.9573 and 0.9509, respectively, both of which are close to 1.0. The regression model has a good fitting degree and can predict the pressure ratio of the system. The SNR is the ratio of signal to noise and is used to measure the ratio of information that can be explained to information that cannot be explained. When the SNR of the model is greater than 4, it is generally considered reasonable. As can be seen from the table, the SNR of this model is 53.797, indicating that the model is reasonable and feasible. According to the condition of probability P less than 0.05, the main parameters affecting the pressure ratio of the system are position, pipe diameter, the interaction term between position and length, position and pipe diameter, length and pipe diameter, and the quadratic term between position, length and pipe diameter. It can be found that the probability, P, value of the length term is greater than 0.05, indicating that the length term has no significant influence on the pressure ratio of the system. In this case, A, B, C, D, AB, AC, BC, A^2, B^2, and $C^2$are significant terms of thermoacoustic model.

Response regression model

The normal distribution of system pressure ratio residuals under the regression model is shown in fig. 2. As can be seen from the figure, residuals are evenly distributed on both sides of the diagonal, indicating that the distribution of residuals meets the random normal distribution. The range of residuals is –3 to 3, and most of them fall near 0, indicating that the model can be well used for pressure ratio prediction and parameter analysis. Based on ANOVA and the interaction between parameters, a second-order regression model of pressure ratio, p_r, can be obtained within the parameter design range:

$$p_r = -2.9277\text{-}45432 \times A + 0.1483 \times B - 0.7211 \times C + 0.1120 \times A \times B +$$
$$+0.9459 \times A \times C + 0.0131 \times B \times C + 0.2337 \times A^2 - 1.6703E-03 \times B^2 + 0.2211 \times C^2$$

Table 4. Variance analysis of system pressure ratio

Sources of variance	Quadratic sum	DoF	Variance	*F* value	Probability, *P*	Significant
Model	10.30	19	0.54	149.72	<0.0001	*
A	0.52	1	0.52	142.70	<0.0001	*
B	4.00E-03	1	4.00E-03	1.10	0.296	
C	0.020	1	0.020	5.64	0.0191	*
AB	0.24	1	0.24	65.98	<0.0001	*
AC	0.10	1	0.10	27.92	<0.0001	*
BC	0.18	1	0.18	50.16	<0.0001	*
A^2	0.039	1	0.039	10.83	0.0013	*
B^2	0.41	1	0.41	112.34	<0.0001	*
C^2	0.15	1	0.15	41.84	<0.0001	*
Residual	0.46	127	3.62E-03			
The total deviation	10.76	146				
SNR = 53.797						
Correlation coefficient = 0.9573				Adjustment coefficient = 0.9509		

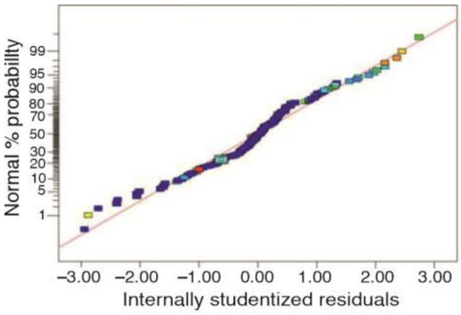

Figure 2. Normal distribution of the residuals of the regression model

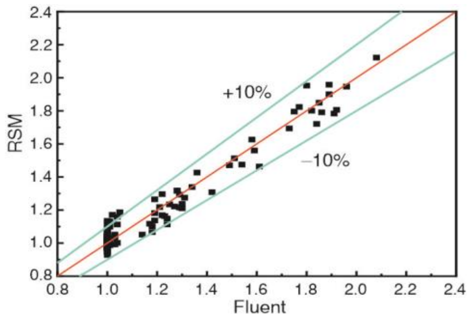

Figure 3. Comparisons between the predicted value of RSM and the calculation result of Fluent

Comparisons between the predicted values of RSM and the calculated results are presented in fig. 3. As can be seen from the figure, the pressure ratio of the system, except for a few points around 1.0, the rest of the points fall within the error range ±10%, which shows that there is a pretty good agreement between actual and predicted values. It indicates that the RSM regression model can be used to predict the pressure ratio of the system well.

Interaction analysis of parameters

The influence of length and position on system pressure ratio under a certain pipe diameter is shown in fig. 4(a). As can be seen from the figure, at the position of the section at room temperature, the pressure ratio first increases and then decreases with the increase of the pipe fitting length. When the length is 100 mm, the pressure ratio reaches the peak. At the position of low temperature section, the interaction between pipe length and position is not obvious. As can be seen from the figure, when the pipe fitting position is close to the normal temperature end and the pipe diameter is large, the pressure ratio reaches the maximum value. When the pipe fitting is close to the low temperature end, the interaction between pipe diameter and position has no obvious effect on the pressure ratio of the system. Therefore, reducing the pipe diameter and installing the pipe fitting close to the low temperature section can help to suppress the pressure oscillation of the system. Figure 4(b) shows that when the control pipe is placed in the low temperature range, regardless of whether the pipe is a contraction or expansion type, the pressure ratio of the system is 1.0, indicating that the system is in an AD state, where the pressure ratio is the ratio of maximum pressure to average pressure. When the regulating pipe fittings are located in the room temperature range, the results of the regulation are shown in two situations depending on the type of pipe fittings. When the pipe fittings are contraction type, the system pressure ratio is 1.0, which means zero oscillation state. When the pipe fittings are expansion type, the system pressure ratio is greater than 1.0, indicating an oscillation state. From this, it can be seen that compared to the pipe diameter, the occurrence of AD is more sensitive to the position of the pipe fittings in the system. The influence of pipe diameter and length on system pressure ratio under a certain position is shown in fig. 4(c). As can be seen from the figure, the interaction between pipe diameter and length has no significant influence on pressure ratio, so the influence of position and pipe diameter should be given priority in the design.

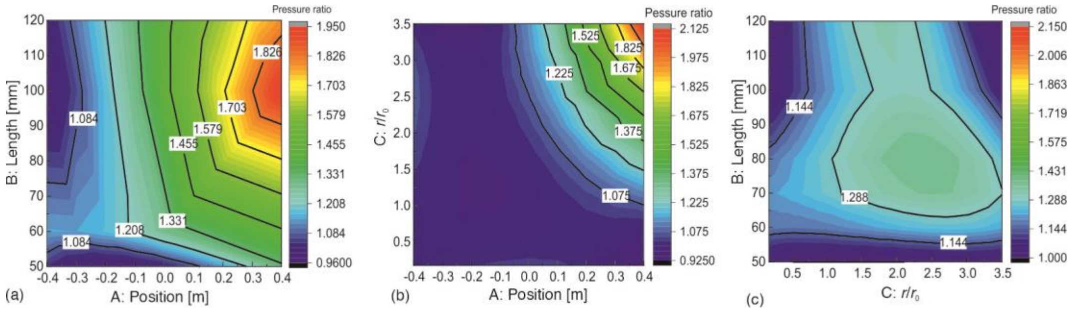

Figure 4. Influence of parameter interaction on system pressure ratio; (a) length and position, (b) pipe diameter and position, and (c) pipe diameter and length

Conclusion

This paper puts forward a kind of a contraction or expansion pipe structure of the cryogenic system oscillation behavior regulation and clarities of the radius of the tube structure, length and position of the impact on the system oscillation state, the introduction of the response surface method, the regression model and parameter interaction effect. The main conclusions are as follows.

Analysis of variance showed that the correlation coefficient and adjustment coefficient are close to 1.0, SNR is high, and the fitting degree of regression model is good. Single factor position, pipe diameter, interaction terms between position and length, position and pipe diameter, length and pipe diameter, and quadratic terms between position, length and pipe diameter have significant effects on system pressure ratio. The prediction error of RSM regression model for pressure ratio is within ±10%, and the distribution of residuals satisfies the random normal distribution, which can predict the system performance within the range of parameter design. The interaction effect analysis shows that the interaction between pipe diameter and length has no significant effect on the oscillation state, so the influence of position and pipe diameter should be given priority in the design.

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