ISSN: 0974-5823 Vol. 7 No. 1 January, 2022

International Journal of Mechanical Engineering

Experimental study of vibration in metal expansion bellow under the effect of flow temperature

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Abstract

In this paper, an experimental study was investigated to analyze the vibration in metal expansion bellows (304 L) typed U-shaped under the effect of various flow temperature and mass flow rate in case of simply- simply support. Two groups of expansion bellow with inner diameter 10mm and 20mm were prepared in various lengths and number of convolutions. The first group represents the inner diameter 10mm at [100mm length (36 convolutions), 200mm length (75 convolutions) and 300mm length (111 convolutions)]. While, the second case represents 20mm inner diameter at [100mm length (25 convolutions), 200mm length (54 convolutions) and 300mm length (82 convolutions)]. The experiments results show that the frequency of bellow was generally increased with increasing the flow temperature. In diameter 10 mm and length 100mm, the frequency was recorded a maximum value about 208.3 Hz at 1 LPM when the temperature increased from 32ºC to 80 ºC. While, in case of 20mm the maximum value of frequency was recorded about 115.5Hz at the same mass flow rate and length. In addition, response surface methodology (RSM) was used to study the effect of three experimental parameters (bellow length, temperature and mass flow rate of water) and their interactions on the response in term of frequency of bellow. The regression model was used as a two factor interaction (2FI) to optimize the result using D-optimal design. The results of regression model show a good agreement with experimental data with the values of coefficient determination R-squared (0.9427) and coefficient determination Adjuster R-squared (0.9115). According to the optimum conditions of model, the minimum value of frequency (88.89) was achieved at bellow length 300 mm, water temperature 56 ºC and water mass flow rate 7.5 LPM.

Keywords: Bellows, Frequency, convolution, RSM.

1. Introduction

Bellows are a corrugated tubes with a thin wall and have a strong degree of flexibility when exposed to a range of load conditions [1]. Bellows are made of material with a comparatively thin gauge such as stainless steel and are convoluted to have the required stability to absorb mechanical and thermal movements encountered in operation. The convolutions of bellows have a Varity shape: S-shaped, C-shaped, and U-shaped [2-3]. Bellows expansion joints are commonly used in pipe structures for thermal expansion absorption, pressure, flow containment, oil refineries, chemical stations, nuclear power plants, and residential and commercial heating and cooling systems [3]. Piping vibration failure is one of the primary causes of breakdowns, fires and explosions in piping systems [4]. Vibration is the rapid back and forth movement (or up and down movement) around a point of equilibrium. The amount of back-and-forth motions per second is referred to as its frequency[5]. Vibration can be classified into the following categories: Free Vibration occurs if a system is left to vibrate on its own while, the forced Vibration occurs as a result of external stress on the device. The forced vibration is classified into two types (un-damped vibration; if no energy is lost during oscillation) and (damped vibration; if any energy is lost). In addition, the deterministic and random vibration occurs if the value or magnitude of the excitation (force or motion) acting on a vibratory device can be determined at any point in time. Various studies have been conducted on the vibration of a pipe conveying liquids. Such as, Yih-Hwang and Chih-Liang [6] used a finite element method to deal with the vibration and control analyses of Timoshenko pipes conveying fluid. The results indicate that a critical damping design can be achieved for the targeted mode controlled. Lee and Chung [7] analyzed the vibration in a straight pipe conveying fluid in case of fixed at both ends using new non-linear model. The natural frequency computed from the linearized equation while, time of displacement calculated by applying the generalized- α time integration method. As validated with the previous studies, the new model is more reasonable than PamKdoussis' model due to its ability in description the coupled non-linear motion for the longitudinal and transverse displacements in more accurate. In study of [8], a numerical solution of dynamic stability for a curved pipes conveying fluids was investigated to obtain the flow velocity and a non-dimensional circular frequency. The results show a good coincidence with the results of matrix method by Lolov & Lilkova-Markova. Veerapandi et al. [9] studied and analyzed the natural frequency in pipe conveying fluid using mathematical model and computational analysis and validate their results with experimental study. Mao Qing et al. [10] studied the natural frequencies, the fluctuating pressure and structure acceleration response in the pipeline flow under the effect of flow conditions and orifice ratios. The results show that the higher the flow rate, the greater the intensity of the fluctuating pressure. Sugiyama et al.[11] investigated a numerical study of the stability for a cantilevered tubular pipe conveying fluid under the effect of an intermediate lateral spring support. The results of study show that the stabilizing effect due to a spring can be caused by transition of the instability mechanism from flutter to divergence. Precise integration method used by [12] to investigate the dynamic analysis of supported pipes conveying pulsating fluid in Hamiltonian system. Using several numerical examples show that the method is rapid and an efficient for dynamic analysis in pipes. Avinash B. Kokare et al.[13] presented a finite element method to evaluate the velocity and pressure of steel straight pipe depending on the natural frequency. The results show that the natural frequencies decrease with increasing the pipe thickness in case of Clamped-Free boundary conditions. On the contrary, the natural frequencies increase with increasing the pipe thickness in case of clamped-clamped boundary conditions. Muhsin J. Jweeg et al.[14] used Galerkin’s methods to provide natural stability and frequency of pipes conveying fluid at different boundary conditions and velocities. The results conclude that the natural frequencies decrease with increasing of the fluid velocity. Nabeel. K. Abid et al.[15] derived a new analytical model to investigate the effects of residual stresses at girth welds of a pipe on the vibration characteristics and stability. On the other side, experimental rig was built to fulfill the required investigations at different condition. The theoretical and experimental results prove that the residual stresses due to welding reducing natural frequencies for both clamped-clamped and clamped-pinned pipe conveying fluid. In addition, the two conditions were stable at small flow velocity and loss the stability at super critical velocity. Jin-Bong et al.[16] Studied the effects of convolution geometry at different boundary conditions on the failure of bellows. As mentioned in the analysis of study results, the principal stress increases and the number of load cycles to failure decreases linearly as the inner radius of the bellows and of deflection at the bellows end increase. T.Y.Chen et al. [17] applied a digital-image-correlation method to measure the stiffness of single and double-ply bellows under the influence of the internal pressure on the stiffness of the bellows. The results show that tensile meridian and hoop strains on the single-ply bellows are found as expected. Satoshi Igi et al.[18] proposed a new type of convolution called double convolution bellows to examine the deformation behaviors under repeated axial loading, internal pressurizing and torsional loadings. The results show an improvement in thickness distribution, instability and torsional flexibility. Weaver and Ainsworth [19] carried out experiments on the flow -produced vibrations in bellows with a diameter of 20 mm and discovered large-amplitude flow-excited vibrations at velocities above 4.5 m/s under perfect upstream flow conditions. Zheng et al. [20] Built a three-dimensional numerical method based on RPI boiling model and vibration model to investigate the influence of tube vibration on boiling flow with LH2. The numerical results indicate that the vibration can significantly enhance the convective heat flux while weaken the quenching heat flux and the evaporative heat flux. Gawande et al. [21] performed analytical, numerical simulation and experimental investigations to find the axial natural frequencies of bellows. The effect of number convolutions on the deformation and axial natural frequency response were obtained under different end conditions. The results seen that the range of axial natural frequencies recorded maximum deformation with less number of convolutions and minimum values with a large number of convolutions. The main objectives of this study was investigated an experimental study to analyze the vibration in metal expansion bellows (304 L) typed U-shaped under the effect of various flow temperature and mass flow rate in case of simply-simply support. In addition, response surface methodology (RSM) was used to study the effect of three experimental parameters (bellow length, temperature and mass flow rate of water) and their interactions on the response in term of frequency. The regression model was used as a two factor interaction (2FI) to optimize the result using D-optimal design.

2. Experimental Description

2.1 Fabrication of expansion bellows

In this experimental test, two groups of expansion bellow 304 L type U-shaped were prepared in various lengths and number of convolutions using tungsten arc welding (Tig) as shown Figure 1. The first group represents the inner diameter 10 mm with three cases of (100 mm length @ 36 convolutions, 200 mm length @ 75 convolutions and 300 mm length @ 111 convolutions). While, the second group represents the inner diameter 20 mm with (100 mm length @ 25 convolutions, 200 mm length @ 54 convolutions and 300 mm length @ 82 convolutions). The material specifications of below and the details of samples were shown in Table 1 and the chemical composition of bellow material were tested and represented in Table 2.

Figure 1 . Scenarios of expansion bellows

Table 1. Specifications of expansion Bellows

Parameter	**Bellow(1)**	**Bellow(2)**
Expansion joint material	St. St. 304 L	St. St.304 L
Modulus of elasticity	193000 N/mm^2	193000 N/mm^2
Bellow Yield stress	215 N/mm^2	215 N/mm^2
Poisson's ratio	0.275	0.275
Bellow type	U-Shaped	U-Shaped
Length of expansion bellow	100, 200, 300 mm	100, 200, 300 mm
Outer diameter	13.6	25.2 mm
Inner diameter	10 mm	20 mm
Thickness	1mm	1 mm
Convolution depth	0.8 mm	1.6 mm
Convolution pitch	2.5 mm	3.8 mm
Total number of Convolution	36,75,111	25,54,82
End tangent length	40 mm	15 mm

Table 2. Chemical composition of Bellow material

C %	**Si %**	**Mn %**	**P %**	**S %**	**Cr %**	**Mo %**	**Ni %**	**AL %**	**C0 %**	**Cu %**	**Fe %**
0.042	0.61	1.36	0.0060	0.0020	23.66	0.0070	6.38	0.0040	0.0113	0.089	67.5

2.2 System description

In order to achieve the main objectives of this study, a test system was built and install as shown in Figures 2. According to the schematic diagram of the system in Figure 2, the system consists from a number of parts named as: test section, storage tank, pump, supports, piping and fitting. The test section was fabricated to easily replace the expansion bellows. A storage tank was used with 50 L capacity and with electrical heater 1200 W. In addition, a safety valve was fixed at the top of the tank to use in case of overpressure. To circulate the heating water between the tank and the test section, a water pump was used with maximum flow 33 LPM, 12 m head and 1.2 bar working pressure. A set of fitting equipment were used to complete the installation and assembly of the system. For example, the ball valve used to control the flow of water. A number of supports was fabricated from steel to use in testing of the system in cases of free-fixed and fixed-fixed. Two triple connections were used before and after the test section to install the pressure sensors.

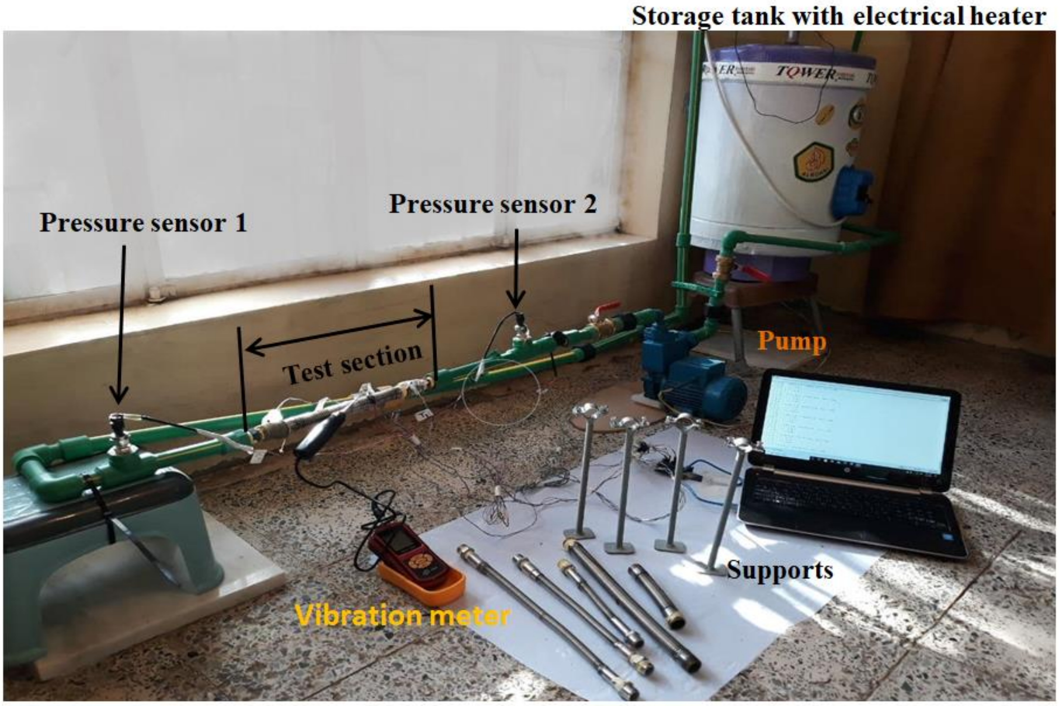
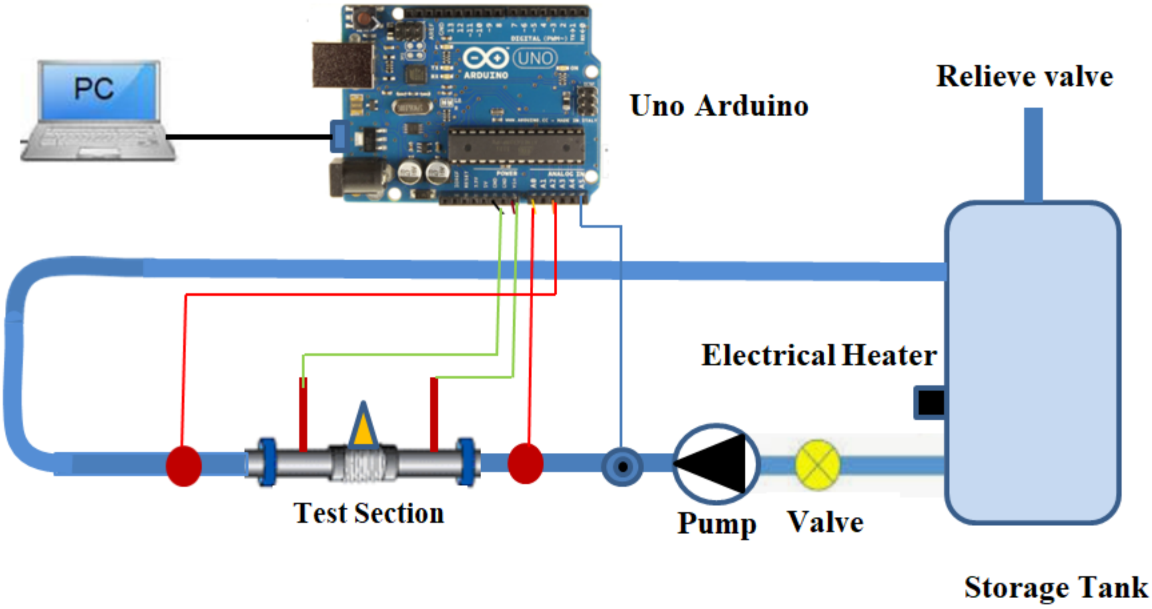


Figure 2. Photograph of system



◉	Flow rate sensor	●	Pressure sensor
▮	Temperature sensor	▲	Vibration sensor

Figure 3. Sketch diagram of the system

2.3 Measurements and instrumentations

A set of instrumentations are connected to observe the input and output parameters including the temperature, pressure, flow rate and the acceleration. Two digital thermometers type DS18B20 ranged between (-55 to +125) °C with an accuracy ±0.5°C was installed to measure the water temperature before and after the inlet and outlet of section test. Water flow sensor model YF-S201 with flow rate ranged between (1 to 30) LPM and with an accuracy about ±10% was installed to measure the water mass flow rate. The water flow sensor operates with liquid temperature and pressure until 120°C and 1.7 MPa. In addition, two pressure sensors type PIA (0 to 16) bar were installed before and after the inlet and outlet section test. Vibration meter GM63B (Piezoelectric ceramic accelerometer (shear-type) was used to measure and represent the behavior of the expansion below as acceleration, velocity and displacement. The specifications of vibration meter is concluded by: the range of acceleration is 0.1 to 199.9 mm/s^2, the range of velocity is 0.1 to 199.9 mm/s and the range of displacement is 0.001 to 199.9 mm/s with measurement accuracy ±5% ± 2digits and measurement frequency of velocity and displacement 10Hz～1KHz. The data obtained from experimental measurement are collected by uno-arduino and then send to the computer.

2.4 Methodology of Design Expert

Design expert software version 6.0 was used for multiple regression analysis, analysis of variance (ANOVA), and analysis of ridge maximum of data in the response surface regression (RSREG) procedure[22]. The goodness fit of the model in this software is evaluated by the coefficient of determination R^2 and its statistical significance that is checked by the F-test. Each variable to be optimized was coded at two levels -1and +1. Two factor interaction (2F1) regression model was assumed for predicting individual Y variables. The model proposed for each response of Y is:

$$Y = \beta_0 + \sum \beta_i x_i + \sum\sum \beta_{ij} x_i x_j + ei \qquad (1)$$

Where: Y is the predicted response, β_0, β_i, and β_{ij} are a constant linear and interaction regression coefficient terms, x_i and x_j are independent variables, i and j are the index numbers for factors and e_i is the residual error.
Design-Expert bases its numerical optimization on an objective function called desirability. The overall desirability (D) is the multiplicative mean of all individual desirabilities (d_i) that range from 0 to 1.

$$D = \left(d_1 \times d_2 \times \ldots\ldots d_3\right)^{1/n} = \left(\prod_{i=1}^{n} d_i\right)^{1/n} \qquad (2)$$

Where: n is the number of responses. If any of the responses fall outside their desirability range, the overall function becomes zero.

3 Results and discussion

3.1 Results and discussion of experimental part

This study was experimentally investigated to analyze the effect of flow temperature on the frequency in expansion bellows. The experiments tests took in consideration the effect of some design parameters of expansion bellow (inner diameter, length and number of convolutions). In addition the effect of mass flow rate was analyzed and briefly discussed. In general, the frequency increased with increasing the temperature regardless of design parameters but the frequency rapidly increased at small mass flow rate 1 LPM when the inner diameter 10 mm with length 100 mm and number of convolutions 36. Where, the maximum value of frequency was recorded about 208.3 Hz, 160.5 Hz and 136.5 at length 100 mm, 200 mm and 300 mm respectively as shown in Figure 4. In other words, the maximum percentage of increasing the frequency was about 40.7% when the temperature changed from 32 ^{o}C to 80 ^{o}C in length 100 mm. This can be explained as the increasing of temperature leads to increase the kinetic energy of flow which lead to increasing the vibration in bellow. In the same manner, the frequency in the bellows of diameter 20 mm was also increased but at lesser percentage than the bellows of 10 mm diameter as shown in Figure 5. As appear, the maximum value of frequency was recorded about 115.5 Hz at length 100 mm and constant mass flow 1 LPM with increasing percentage about 9.7%.

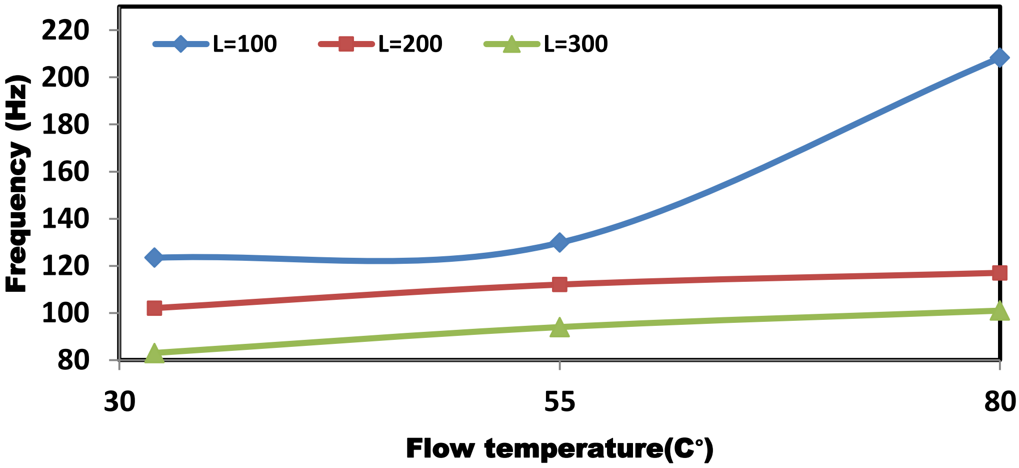


Figure 4. Variation of frequency with flow temperature at inner diameter 10 mm and mass flow rate 1 LPM at different length of expansion bellow.

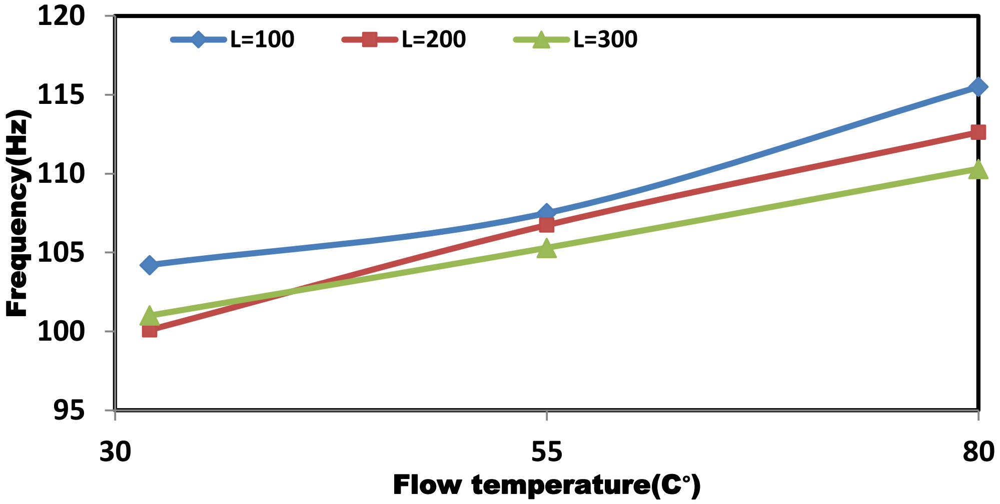


Figure 5. Variation of frequency with flow temperature at inner diameter 20 mm and mass flow rate 1 LPM at different length of expansion bellow.

When taking into account the increasing of water mass flow rate, the trend of frequency was still the same but the percentage of increasing was dropped to 26.9% in inner diameter 10 mm and length 100 mm when the mass flow rate changed from 1 LPM to 14 LPM as shown in Figures 6 and 7. While, in case of inner diameter 20 mm, the percentage of increasing the frequency was increased to 19.2% when the mass flow rate changed from 1 LPM to 14 LPM as shown in Figures 8 to 9.

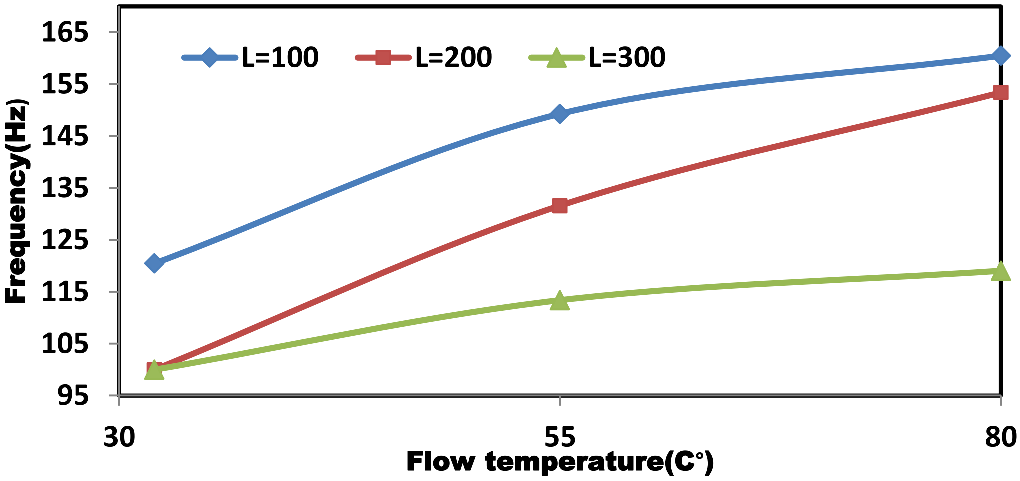


Figure 6. Variation of frequency with flow temperature at inner diameter 10 mm and mass flow rate 7 LPM at different length of expansion bellow.

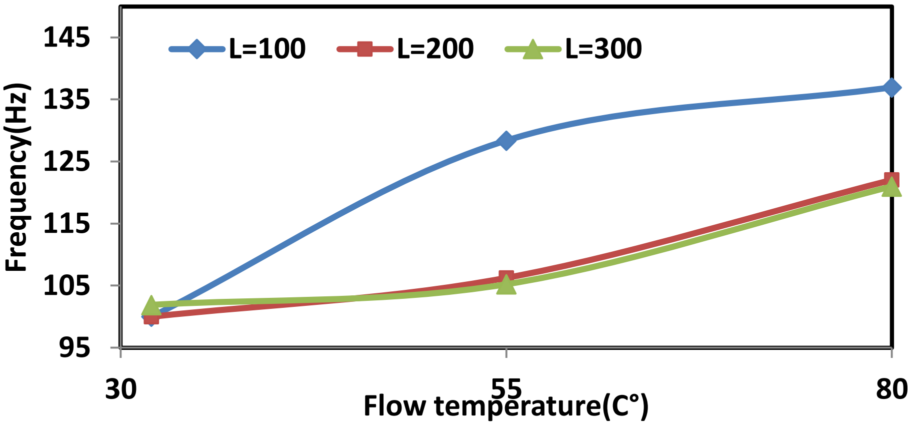


Figure 7. Variation of frequency with flow temperature at inner diameter 10 mm and mass flow rate 14 LPM at different length of expansion bellow.

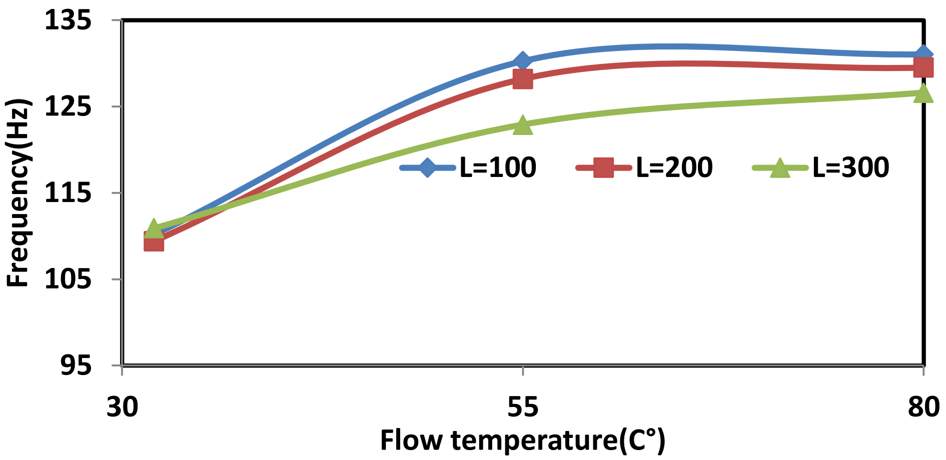


Figure 8. Variation of frequency with flow temperature at inner diameter 20 mm and mass flow rate 7 LPM at different length of expansion bellow.

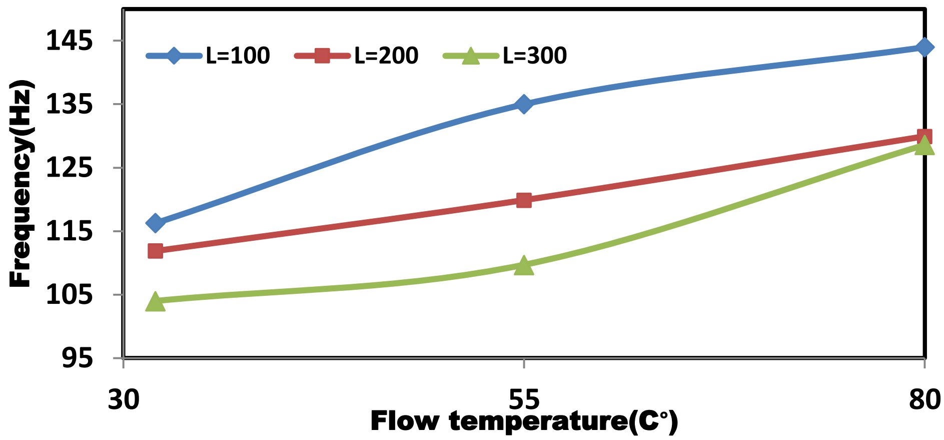


Figure 9. Variation of frequency with flow temperature at inner diameter 20 mm and mass flow rate 14 LPM at different length of expansion bellow.

3.2 Analysis of RSM model

Response surface methodology (RSM) was used to study and optimize the effect of three experimental parameters (bellow length, temperature and mass flow rate of water) and their interactions on the frequency in expansion bellow. The regression model was proposed as a two factor interaction (2FI) to optimize the result using D-optimal design. The coefficient of determination, R^2 and coefficient of adjusted determination Adj-R^2 were used to validate of the polynomial model. While, the F-test and the adequate precision ratio were used to investigate the statistical significant.

a) Design of experiment Model

The levels and ranges of independent variables that used in experimental test were (100, 200 and 300) mm for bellow length, (32, 55 and 80) °C for water temperature and (1, 7 and 14) LPM for water mass flow rate as shown in Table 3. While, the design data and the response of the model represented in Table 4. As shown in Table, the maximum absolute error between the predicted and actual frequency was recorded 13.7%. This indicate that the model has an adequate precision.

Table 3. Design summary

Independent variables		**Ranges**	**Variables levels**	
			-1	+1
Length (mm)	**A**	**100-300**	**100**	**300**
Mass flow rate (LPM)	**B**	**1-14**	**1**	**14**
Temperature (°C)	**C**	**32-80**	**32**	**80**

Table 4. Experimental Design of the Independent Variables and the response values

Std.	**Run No.**	**Experimental Variables**	**Response Frequency (Hz)**	**Absolute error**

		Length (mm)	**Mass flow rate (LPM)**	**Temperature (ºC)**	**Actual**	**Predicted**	**%**
13	1	100.00	14.00	32.00	128.21	122.65	4.33
8	2	200.00	1.00	56.00	120.48	119.39	0.904
7	3	300.00	7.50	56.00	83.33	71.89	13.72
6	4	200.00	7.50	80.00	101.00	106.38	5.32
5	5	100.00	1.00	80.00	208.33	202.36	2.86
3	6	300.00	1.00	32.00	153.40	144.30	5.93
10	7	300.00	14.00	32.00	113.39	102.16	9.903
1	8	100.00	14.00	56.00	112.36	126.02	12.15
14	9	100.00	14.00	80.00	123.46	123.47	0.008
15	10	200.00	1.00	56.00	101.20	110.98	9.66
17	11	100.00	1.00	80.00	100.00	100.64	0.64
18	12	300.00	14.00	80.00	131.60	132.62	0.775
9	13	100.00	1.00	32.00	101.01	96.24	4.72
4	14	300.00	1.00	80.00	136.99	149.05	8.80
11	15	200.00	7.50	32.00	112.36	126.02	12.15
12	16	150.00	7.50	56.00	123.46	123.47	0.008
2	17	300.00	14.00	80.00	208.33	202.36	2.86
16	18	100.00	1.00	32.00	120.48	119.39	0.904

The coefficients of the model term were determined by performing the analysis of the polynomial regression as shown in Equation 3. It is observed that the bellow length and water mass flow rate have negative influence and water temperature has positive influence on the frequency of bellow. This mean that the frequency decreased with increasing the length of bellow and the water mass flow rate. On the contrary, the frequency increased with increased the temperature.

$$Frequency = +122.47 - 20.31 * Bellow\ length - 3.55 * Mass\ flowrate + 21.83 * Temperature + 16.58 * Bellow\ length * Mass\ flowrate - 11.1 * Bellow\ length * Temperature - 6.52 * Mass\ flowrate * Temperature$$

(3)

The data were analyzed to check the normal probability plot between the predicted and actual values of frequency. As shown in Figure 10, it can be observed that all points of plot have close place on a straight line implying that the errors are distributed normally.

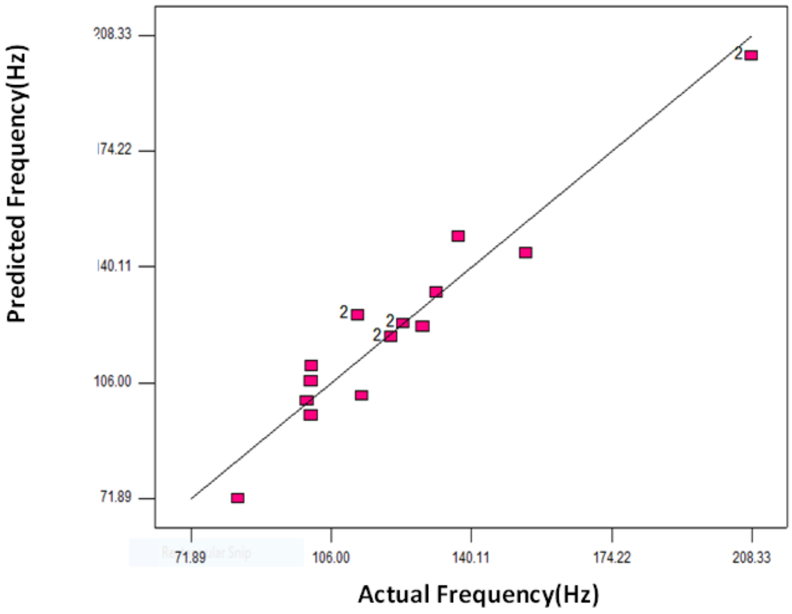


Figure 10. Normal Plot of Experimental and Predicted Values

b) Analysis of variance (ANOVA)

The details of ANOVA table was conducted by fitting equation (3) to the experimental data to determine the regression coefficients and statistical significance as shown in Table 5. The sum of squares, mean square, degree of freedom (DF), P-value and F-value were calculated as indices to analyze the model. The significance of the model terms was assessed by F-ratio at a probability (p) of 0.01. Model adequacies were determined using model analysis, lack of fit test, coefficient of determination (R^2) and adjusted coefficient of determination (R^2). The Probability > F for the model is less than 0.01 except the effect of interaction between the mass flow rate and the temperature is less than 0.05. while, the effect of mass flow rate is not significant. As shown in table, The main effect of linear order of temperature and expansion length were the most significant factor associated frequency. Apparently in Table 5, the lack of fit and pure error for frequency are the lowest with R^2 and adj. R^2 are 0.9427 and 0.9115 respectively. The values of coefficients determination were nearly close to 1 which means that the model is a suitable. In other words, the RSM model could estimate 94.27% of the variability in the frequency.

Table 5. ANOVA for Response Surface 2FI Model

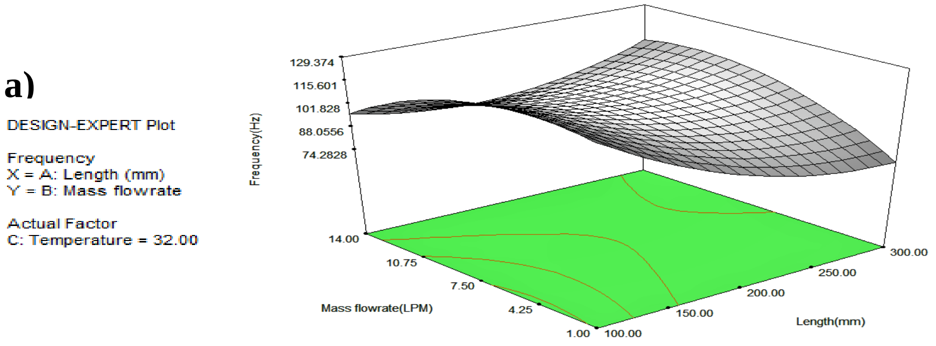
Predictors	**Sum of square**	**DF**	**Mean square error**	**F-value**	**Prob.**	**Nota.**
Model	18311.02	6	3051.84	30.18	0.0001	*
	Linear					
A	5220.88	1	5220.88	51.63	0.0001	*
B	163.38	1	163.38	1.62	0.2299	***
C	5929.88	1	5929.88	58.65	0.0001	*
	Interaction					
AB	3099.42	1	3099.42	30.65	0.0002	*
AC	1224.80	1	1224.80	12.11	0.0051	*
BC	422.84	1	422.84	4.18	0.0455	**
Residual	1112.24	11	101.11			
Lack of fit	1112.24	7	158.89			
Pure error		4				
Core total		17				
R^2	0. 9427					
Adj.R^2	0.9115					
	*P<0.01; **P<0.05; ***P<0.1; Nota.=Notability;					

The interactive relationship between the three design parameters and the frequency as a response was assessed using 3D plots of RSM. These plots are represented in Figures 11,12 and 13 as a function of two independent variables and hold the third variable as a constant.

Figure 11 a-c show the 3D plot of frequency under the effect of bellow length and mass flow with constant temperature. It is observed that there the maximum frequency was recorded at minimum length with middle value of mass flow rate. But, the maximum value of frequency was recorded at the temperature reached to 80 °C as shown in Figure 11-a.

Figure 12 a-c show the behavior of frequency under the effect length and the temperature at constant mass flow. It is observed that the interaction between the length and temperature has more effect on the response of frequency. The frequency increased with increasing both the length and temperature. The same behavior was applicable when the mass flow rate change from 1 to 14 LPM.

From Figure 13 a-c, the indication of the effect interaction between the mass flow rate and temperature with constant length shows that no clear interaction between the two parameters. The frequency was dramatically increased with increasing the temperature. While, its change with mass flow rate was recorded a little change.



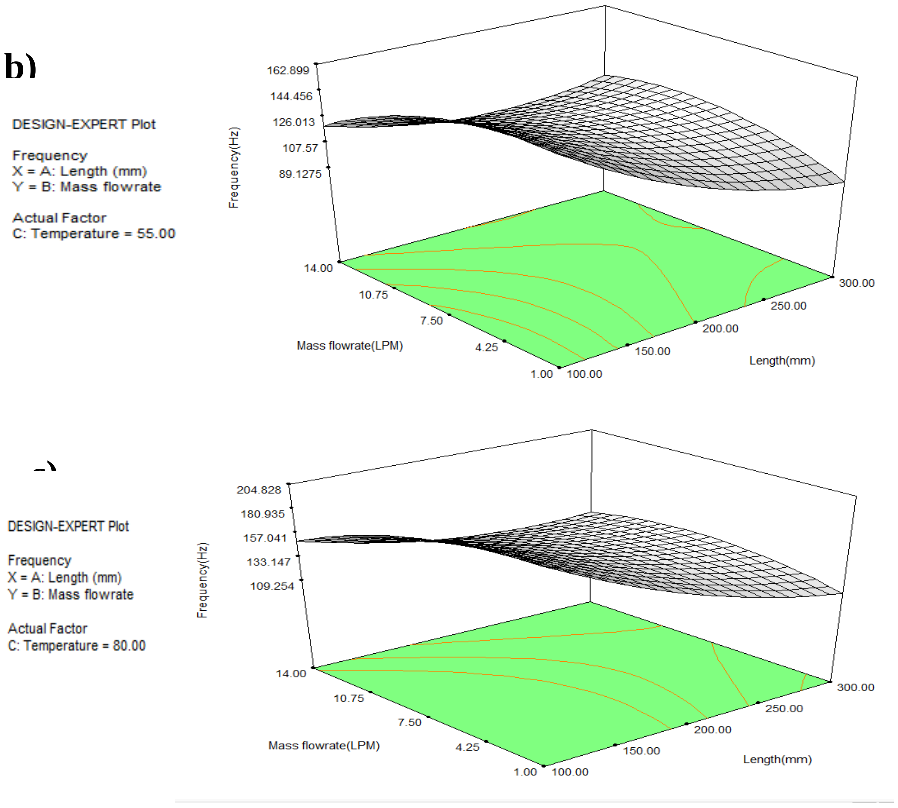
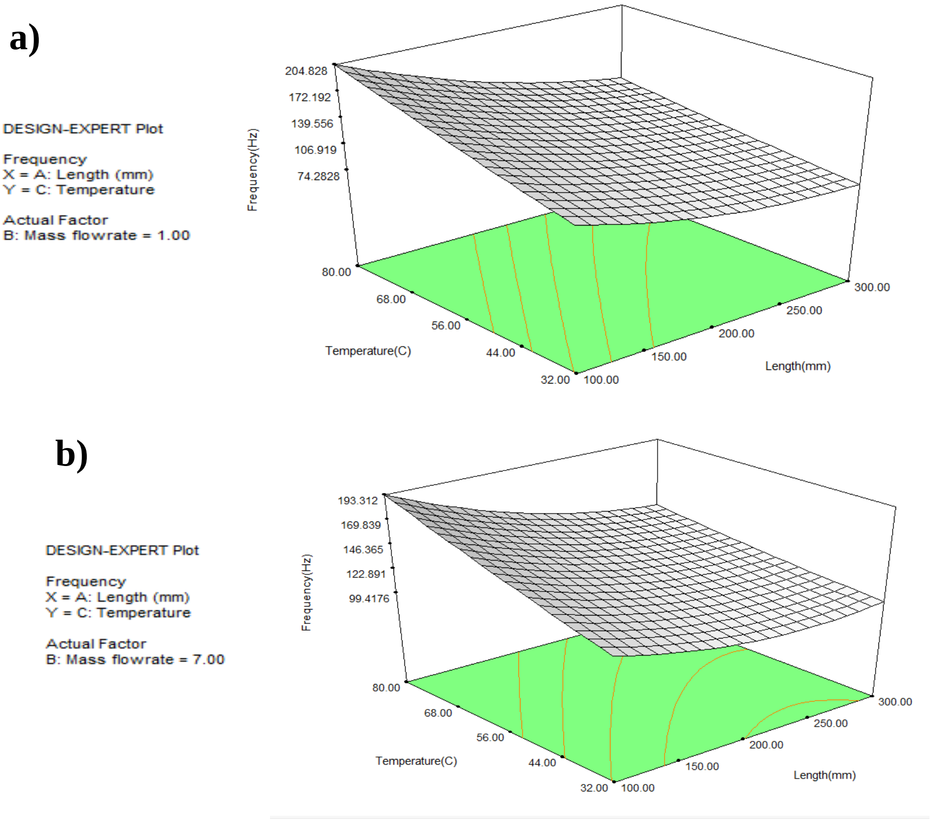


Figure 11. 3D plot of frequency under the effect of interaction between length and water mass flow with constant temperature.



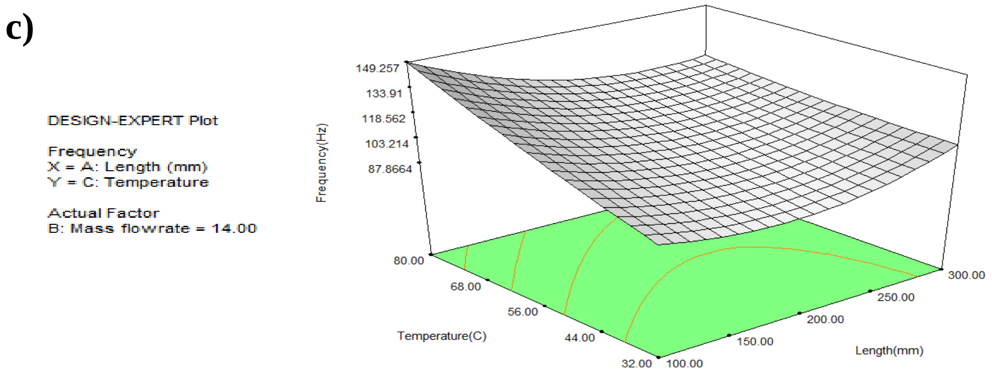


Figure 12 . 3D plot of frequency under the effect of interaction between length and temperature at constant mass flow rate.

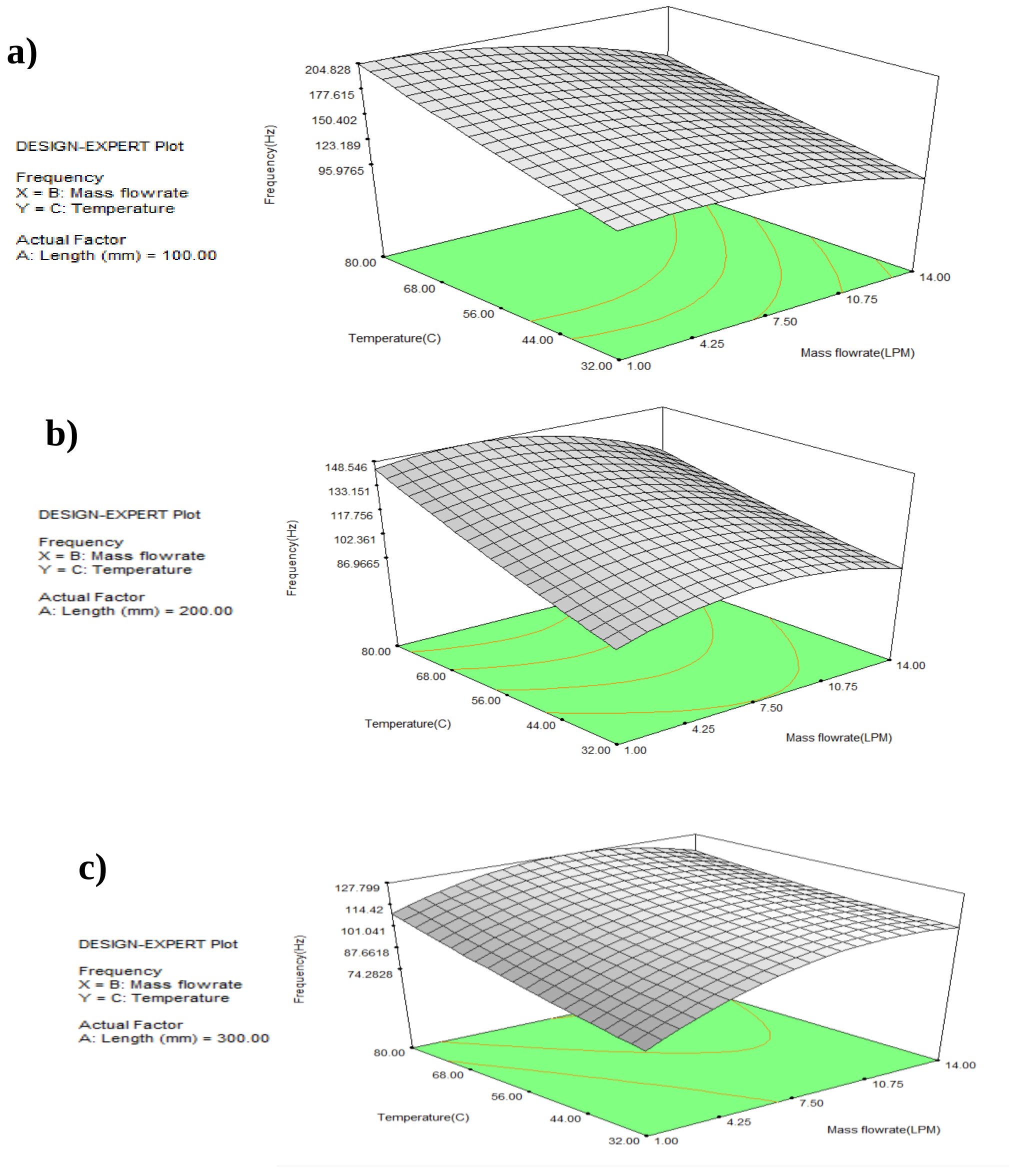


Figure 13. 3D plot of frequency under the effect of interaction between length and temperature at constant expansion length .

C) Optimization process of RSM

Numerical optimization method finds operating conditions (combination of independent variables) that minimizes the frequency, ranging from zero (least desirable) outside of the limits to one (most desirable) at the goal. The desired goal for each independent variable and response was chosen. The independent variables were kept within the range while the responses were set to minimum for frequency. As shown in Figure 14, the minimum value of frequency was investigated at about 300 expansion bellow length, 7.5 LPM mass flow rate and temperature 56 ^{o}C. In case of individual optimization, the responses obtained frequency was found to be 88.89 Hz with minimum desirability 0.992.

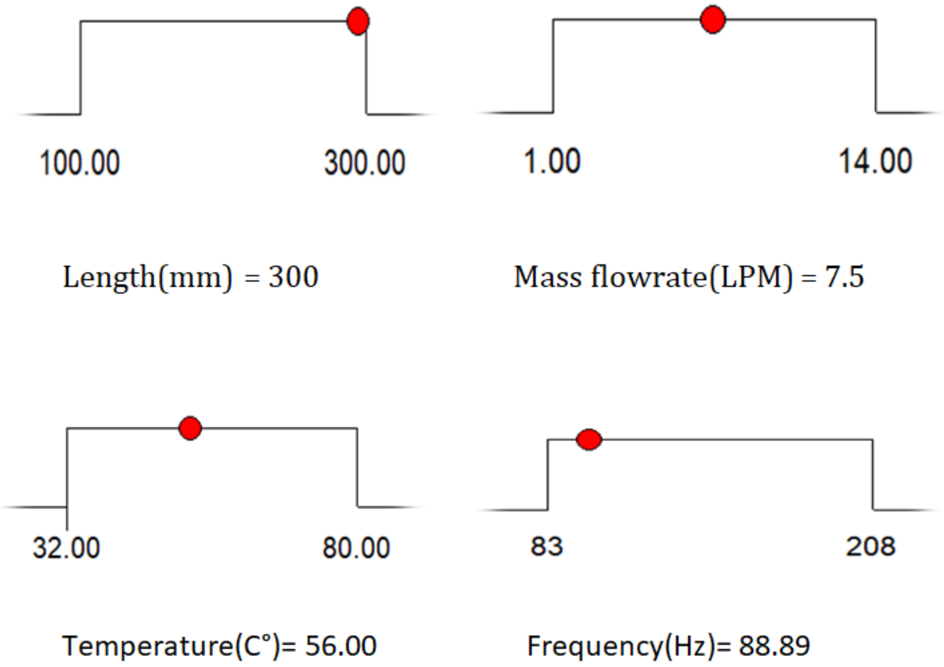


Figure 14. Optimization conditions and response

4. Conclusions

In this paper, an experimental study was investigated to analyze the vibration in metal expansion bellows (304 L) typed U-shaped under the effect of various flow temperature and mass flow rate in case of simply- simply support. In addition, response surface methodology (RSM) was used to study the effect of three experimental parameters (bellow length, temperature and mass flow rate of water) and their interactions on the response in term of frequency of bellow. The regression model was used as a two factor interaction (2FI) to optimize the result using D-optimal design. According to the analysis of the results, the following conclusions are drawn:

1. The frequency of bellow is generally increased with increasing the flow temperature.
2. In diameter 10 mm and length 100 mm, the frequency was recorded a maximum value about 208.33 Hz at 1 LPM when the temperature increased from 32^{o}C to 80 ^{o}C.
3. In case of 20 mm, the maximum value of frequency was recorded about 115.5 Hz at the same mass flow rate.
4. A good agreement with experimental data with the values of coefficient determination R-squared (0.9427) and coefficient determination Adjuster R-squared (0.9115).
5. According to the optimum conditions of model, the minimum value of frequency 88.89 Hz was achieved at bellow length 300 mm, water temperature 56 ^{o}C and water mass flow rate 7.5 LPM.

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