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Research on the Acclimatization Test of Miners at High Altitude and Atmosphere Pressure Compensation in Underground Operations

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Abstract: The purpose of this study was to investigate the appropriate numeric range of atmosphere pressure compensation, which can relieve hypoxia of miners working in high-altitude mines. During the research, Miners' physiological indexes were tested in three stages of acclimatization and the degree of miners' hypoxia was analyzed. Meanwhile, based on the air pressure measured in four underground levels at all seasons, researchers explored the air pressure changes and influence factors. Mathematical models of the atmosphere pressure compensation were also made. The results show the following points: As the time that miners remained in high-altitude mines passed, their anti -hypoxic capability increased and their blood oxygen saturation index could reach to 90.42±3.43 %; the range of atmosphere pressure of underground levels, which was nearly equal indifferent locations of the same face, varied significantly in different seasons and altitudes. And the air pressure in levels changed relatively; the numeric ranges of atmosphere pressure compensation in different levels and seasons were obtained, which provided a new method of calculating the target values of pressurizing or oxygen supplying.

Keywords: *High-Altitude Mine; High-Altitude Acclimatization Test; Air Pressure Change; Atmosphere Pressure Compensation.*

1. Introduction

Nowadays, the difficult problem of key technology expected to be solved about underground operations in plateau lies in anoxia of miners. A series of anoxic symptoms and signs caused by insufficient oxygen supply and terrible construction condition of inside well make labor capability decline obviously. Therefore, in the view of the existing situation, taking protection measurement and improving operation environment to help miners overcome anoxia become essential.

At present, increasing pressure and breathing oxygen are two main ways insuring against anoxia. For example, in the project analysis of strengthening pressure and increasing oxygen in Qinghai-Tibet railways and buses operated by Z.Z. Ouyang [1], through calculating the relation between air tightness of vehicles and leakage amount of air, he put forward three projects: (1) supply oxygen; (2) supply oxygen and strengthen pressure;(3) strengthen pressure; After analyzing projects, the project (1) was recognized as a practical idea because the project (2) & (3) needed high requirement of air tightness and pressure-bearing capacity; in project (2), the performance of air tightness and the requirement of strengthening pressure were equivalent to a high-speed railway of 300 kilometers per hour; in project (3), those were equivalent to pressure-bearing capacity of airplane 16 kPa. In the ventilation construction of underground project in plateau, the special subject explored by X.Y. Sun [2] using Bernoulli equation to analyze methods of adopting press-style ventilation to strengthen pressure and ventilate, he attempted to strengthen pressure in main fans and improve ventilation system to solve the problem of anoxia. S. Xin [3] made a research about mine mountain in plateau at the altitude of about 3850 m (air pressure 63.2 kPa). He adopted technology of strengthening pressure manually, and strengthened return-airway ventilation resistance at the same time, which made the whole ventilation system form a space of strengthening pressure to achieve the goal of increasing air pressure inside mine well. He further put forward that the object parameter of strengthening pressure manually should consider the index of human labor adaptation (altitude level 3000 m) as reference value, which could be adjusted to 3200 m appropriately (air pressure 67.9 kPa).

In the research field of ventilation and oxygen supply of tunnel construction at the high altitude region, Y.S. Liu [4], for tunnel from Gela to Fenghuo Mountain in Qinghai-Tibet Railway with altitude level of inner railway track 4905 m (air pressure 53.9 kPa), developed a comprehensive method combined dispersion oxygen supply and moveable oxygen cabin in tunnel working surface, which could increase the concentration of oxygen in the working area and increase partial pressure of oxygen about 2 to 3 kPa nearby construction region. P. Yang [5-6] and his team, in the Tin-Iron mountain and Lead-Zinc Mine located in the north edge of Qaidam Basin of Hai Xi Region at the altitude of 3050 m (air pressure 70 kPa), put forward a method of increasing oxygen in working face underground non-coal mine well in plateau, that was "the project of oxygenation and ventilation considering the principle of separating membrane to produce oxygen as the core", which used the air source offered by compressor and regarded hollow fibre membrane component as separation equipment and useed the remote centralized pipeline as the equipment of supplying oxygen. Furthermore, he thought that the object of increasing oxygen should regard the content of air at the altitude of 1500 m (air pressure 85.4 kPa) as reference value of equivalent. F. Yao [7], researched the ventilation and oxygenation of tunnel construction in Qinghai-Tibet Railway of Yang Bajin Pleatu at the altitude of 4200 m (air pressure 60.4 kPa). He put forward that the way of solving anoxia of tunnel construction ventilation in plateau was to ensure adequate fresh air in working face and strengthening the amount of ventilation and improving the air volume. Then, he thought that the key point of oxygen supply lay in local part. Each staff should own their oxygen bottle, economical and practical.

The common points above all research lie in strengthening pressure (or supplying oxygen) for underground construction workers in plateau. The desired value of strengthening pressure (or supplying oxygen) is determined mainly by the medical angle and on the premise of improving within little range. But, there is no unified standard in the range and quantity of strengthening pressure (or supplying oxygen). As the view of there is highly discrepancy in degree of anoxia under different construction circumstances at the different altitude level for underground well workers, this text will put forward the range of atmosphere pressure compensation of deserved value about strengthening pressure (or supplying oxygen) by the method of combining miners' acclimatization state [8] in plateau and variation of air pressure inside well.

2. Acclimatization judgment and test analysis of all indexes:

2.1. The object and the method of acclimatization test:

2.1.1. Test object:

As an important aspect of plateau research, the judgment of acclimatization state in plateau is always being taken seriously by various country governments [9]. This research will choose the mining areas at the altitude of 4000 m in Tibet, which is the most suitable environment for miners, as the altitude of test. And miners stay there more than 15 hours on average per day. We take the method of group sampling, and ensure that all testers have the same constitution with the equal ages. The people entering and being stationed 7 days are 10 with the gender from 23 to 29; 30 days are 13 people with the gender from 23 to 30; 180 days are 79 people with the gender from 23 to 30; contrast group are 20 people in plain (Beijing) with the gender from 23 to 28.

2.1.2. Test indexes:

The process of acclimatization test judgment can be divided into 3 stages [10], which are: the initial acclimatization stage (7 days), the basic acclimatization stage (30 days), the complete acclimatization stage (above 180 days); the test indexes include: Breath, plus, systolic pressure, diastolic pressure, blood oxygen saturation.

2.1.3. The way of research:

Select statistical software SPSS18.0 with extreme significance level; adopt the way of $\chi 2$ checking to compare the rate of acclimatization in pairs in all stages [11]. According to the different stages of acclimatization, divide research objects into groups, and make difference test about breath, heart rate, systolic pressure, diastolic pressure and blood oxygen saturation of all levels. Take the analytic way of variance and least significant difference to compare in pairs. Before statistics analysis, make Normality Test (K-S) and Test of Homogeneity of Variance (Levene) for index data of all groups and all types respectively, but for index data out of the requirement of Normality Test (K-S) and Test of Homogeneity of Variance (Levene), deal with the rank transformation analysis of variance [12].

2.2. The result and discussion of acclimatization test:

2.2.1. Breath:

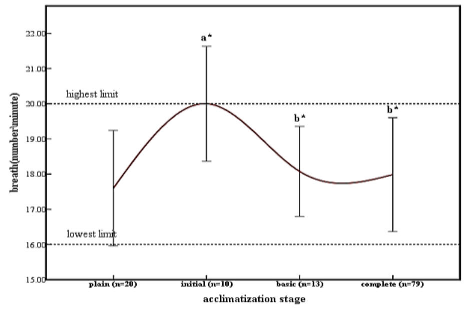


Fig.1: *Model of press-interval series ventilation and air pressure gradient*
a: P<0.01 vs. plain contrast group; b*: P<0.01 vs. the initial acclimatization stage group.*

The Fig 1 shows that there exists extremely significant difference about breath at the initial acclimatization stage between two contrast groups (P<0.01); there exists no extremely significant difference at the basic and complete acclimatization stages between two contrast groups (P>0.05), but exists in extremely significant difference at the initial acclimatization stages between two contrast groups (P<0.01). The result illustrates that normal human's breath frequency in plain area are 16~20 numbers/min and miners' breath frequency increases by (20 ± 0.82 numbers/min) in mining area within 7 days; as the miners stay in mining area longer, their breath frequency declines gradually; after 180 days, their breath frequency (17.99 ± 0.81 numbers/min) comes near to the frequency of the plain contrast group (17.60 ± 0.82 numbers/min).

2.2.2. Heart rate:

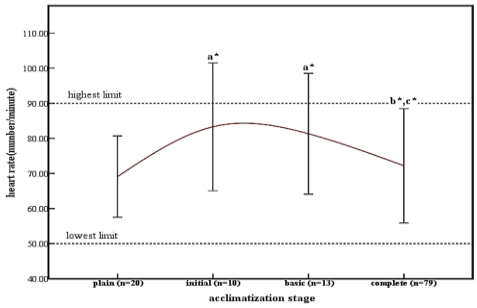


Fig.2 *: The variation of mean value of heart rate in different acclimatization stages (mean ± standard deviation)*

a: P<0.01 vs. plain contrast group; b*: P<0.01 vs. the initial acclimatization stage group; c*: P<0.01 vs. the basic acclimatization stage group.*

The Fig 2 shows that at the initial and basic acclimatization stages, heart rate in plateau is above the plain contrast group (P<0.01); there exists extremely significant difference about heart rate at the initial and complete acclimatization stages between two contrast groups (P>0.05). The result illustrates that heart rate of human body in plain are 50~90 numbers/min and miners' heart rate increases to (83.30 ± 9.10 numbers/min) quickly in mining area within 7 days; after 180 days, their heart rate (72.19 ± 8.14 numbers/min) comes near to the heart rate of the plain contrast group (69.10 ± 5.79 numbers/min).

2.2.3. Blood Pressure:

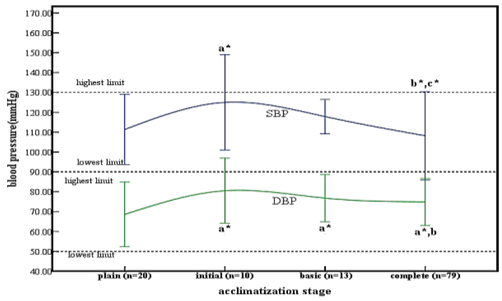


Fig.3: *The variation of mean value of blood pressure in different acclimatization stages (mean ± standard deviation)*

a: P<0.01 vs. plain contrast group; b*: P<0.01 vs. the initial acclimatization stage group; b: P<0.05 vs. the initial acclimatization stage group; c*: P<0.01 vs. the basic acclimatization stage group.*

The Fig 3 shows systolic pressure and diastolic pressure. About the systolic pressure, there exists extremely significant difference at the initial acclimatization stage between two contrast groups (P<0.01); at the basic acclimatization stage, there exists no extremely significant difference between them (P>0.05); at the complete acclimatization stage, there exists no extremely significant difference between them (P>0.05) but exists it at the basic acclimatization stage (P<0.01). About the diastolic pressure, at the initial and basic and complete acclimatization stage, there exists extremely significant difference compared with the plain contrast group (P<0.01); there exists extremely significant difference between at the complete acclimatization stage and at the initial acclimatization stage (P<0.05).

The result illustrates that in the normal condition, the systolic pressure ranges from 90 to 130 mmHg and the diastolic pressure ranges from 50 to 90 mmHg. The systolic pressure statistics result manifests that the systolic pressure (125.00 ± 12.01 mmHg) increases distinctly within 7 days after miners enter mining area, but with the prolongation of living there, it declines to (108.12 ± 11.07 mmHg) 180 days later, which comes near or lowers than the level of systolic pressure of the plain contrast group (111.35 ± 8.80 mmHg). The diastolic pressure statistics result manifests that there exists extremely significant difference compared with the plain contrast group at all 3 stages, and 180 days later the diastolic pressure (74.87 ± 5.91 mmHg) is above the level of diastolic pressure of the plain contrast group (68.60 ± 8.17 mmHg).

2.2.4. Blood oxygen saturation:

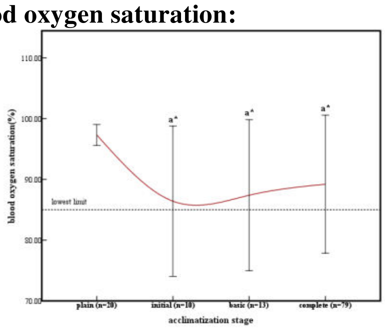


Fig.4: *The variation of mean value of blood oxygen saturation in different acclimatization stages (mean ± standard deviation)*

a: P<0.01 vs. plain contrast group.*

The Fig 4 shows that there exists extremely significant difference about blood oxygen saturation compared with the plain contrast group at all three stages (P<0.01). The result manifests that blood oxygen saturation declines distinctly and are lower than the level of the plain contrast group (97.30 ± 0.86 %) after miners enter mining area at the altitude of 4000 m at all three stages. But, from the Fig, we can see that half a year later, blood oxygen saturation (90.42 ± 3.43 %) goes up distinctly than the initial acclimatization stage.

2.2.6. The anti-hypoxic degree:

Some research materials manifest that [13] [P(A-a)O_2]<20 hPa is normal in the plain area; but in the plateau area, all kinds of influence of improving lung dispersion capability makes [P(A-a)O_2] decline; when altitude level is 2260 m, [P(A-a)O_2]<6.65 hPa; when altitude level is 4280 m, [P(A-a)O_2] comes near to 0 hPa. Judging from this, according to the oxygen dissociation curve [14~16] formula (1), we can get partial pressure of oxygen in alveolar in the different altitude area.

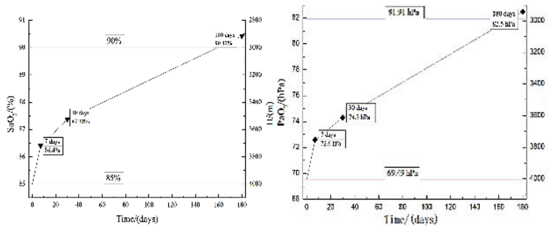
$$SaO_2 = 100 - 67.7 \times e^{-[(PaO_2 - 2.67)/2.71]} \quad (1)$$

In formula, SaO_2 represents blood oxygen saturation, %; PaO_2 represents the blood oxygen partial pressure in artery, hPa.

According to analyzing the oxygen dissociation curve formula (1) of the oxygen partial pressure range (from 26.7 hPa to 133.3 hPa) and alveolus-artery oxygen pressure difference, we can get partial pressure of oxygen in alveolar corresponding to blood oxygen saturation in the conditions of different altitude level areas as Table 1 manifest; the actual value and the theoretical value of blood oxygen saturation and partial pressure of oxygen in alveolar of miners in the three acclimatization stages show as Fig 5.

Table.1: *The variation of mean value of blood oxygen saturation in different acclimatization stages*

Altitude (m)	SaO_2 (%)	PaO_2 (hPa)	$[P(A\text{-}a)O_2]$ (hPa)	PaO_2 (hPa)
0	97	102.48	< 19.06	<121.54
1000	95	92.01	<14.12	<106.13
2000	92	82.37	< 8.11	< 90.48
3000	90	77.80	< 4.11	<81.91
4000	85	69.49	0	69.49



(a) SaO_2 *(b) PaO_2*

Fig.5: *The variation of mean value of blood oxygen saturation and partial pressure of oxygen in alveolar in different acclimatization stages*

From the angle of safety to analyze it, the line where blood oxygen saturation declines to its 75 % is the safety limitation of making casual exercises with control. From the angle of physiology to analyze it, only when blood oxygen saturation is above 85 % can we do manual work. According to Table 1 and Fig 5, in the 7th day, blood oxygen saturation is 86.4 %; in the 30th day, it is 87.38 %; 180 days later, it comes to 90.42 % and the total value increases by 4.02 %, which is near the value of blood oxygen saturation (90 %) at the altitude of 3000 m; in the 7th day, partial pressure of oxygen in alveolar is 72.6 hPa; in the 30th day, it is74.3 hPa; 180 days later, it comes to 82.5 hPa and the total value increases by 9.9 hPa, which is slightly above the theoretical value (81.91 hPa) of partial pressure of oxygen in alveolar at the altitude of 3000 m.

The result manifests that if miners live in the mining area at the altitude of 4000 m for a long time and go through complete acclimatization more than half a year, the volume of oxygen in blood will increase, which is one of important ways that organism compensates oxygen chronically; blood oxygen saturation and oxygen partial pressure in alveolus these two index values come near the index values of the altitude of 3000 m. The air pressure environment index corresponding to anti-hypoxic capability after acclimatization is equivalent to the air pressure environment index of the altitude level of "declining 1000 m".

3. The air pressure judgment and measurement analysis of air pressure in four levels:

3.1. The object and purpose of test:

The measurement of air pressure in mining areas selects four levels, that is 4450 m, 4470 m, 4490 m, and 4510 m, and their functions are reclamation, stope preparation, mine exploitation, transportation. We measure as progressive distance of four levels. The years and months of measurement are April, August, December, January ranging from 2013 to 2014; the time of measurement ranges from 9:00 am to 17:00 pm. The purpose is to observe air pressure variation and influence factors of four levels at spring, summer, autumn, and winter, which will provide a proper range of pressure supply for underground operations of miners.

3.2. The result and discussion of air pressure measurement:

3.2.1. Air pressure variation of four levels:

From Fig 6, we can see that (1) It is measured 122 sample dates in the level of 4450 m and the overall periods of air pressure variation are 3.60 hPa, 3.40 hPa, 2.80 hPa, 3.80 hPa at April, August, December, January; (2) It is measured 125 dates in the level of 4470 m and the overall periods of air pressure variation are 4.20 hPa, 4.00 hPa, 3.80 hPa, 3.30 hPa at 4 seasons; (3) It is measured 109 dates in the level of 4490 m and the overall periods of air pressure variation are 3.40 hPa, 4.00 hPa, 4.00 hPa, 3.80 hPa at four seasons; (4) It is measured 119 dates in the level of 4490 m and the overall periods of air pressure variation are 3.80 hPa, 4.00 hPa, 3.90 hPa, 3.90 hPa at four seasons; the result shows that the overall periods of air pressure variation of four levels inside well reach a state of equilibrium and the average value is (3.73 ± 0.22 hPa); The overall spread of variation equals to the difference between the highest air pressure and the lowest air pressure.

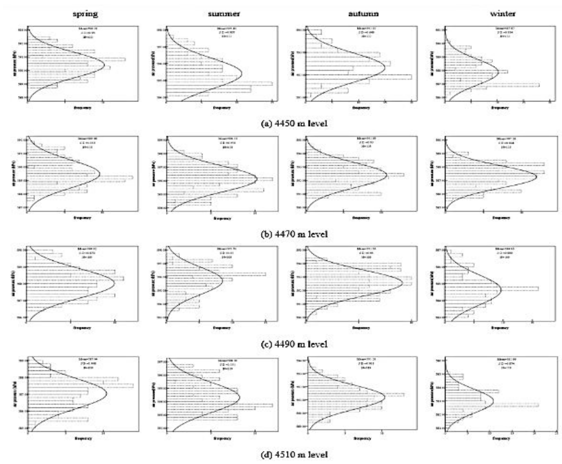


Fig .6: *The atmosphere pressure in four levels at all seasons*

3.2.2. Seasonal air pressure variation:

The Fig 6 shows that measurement data of air pressure in four levels all obey normal distribution. (1) The overall period of air pressure variation in the level of 4450 m yearly is 7.53 hPa; (2) The overall period of air pressure variation in the level of 4470 m yearly is 8.87 hPa; (3) The overall period of air pressure variation in the level of 4490 m yearly is 11.07 hPa; (4) The overall period of air pressure variation in the level of 4510 m yearly is 11.31 hPa. The result manifests that due to the influence of seasonal change, the average value of overall spread of air pressure variation of four levels inside well is (9.70 ± 1.81 hPa). The overall spread equals to the difference between the air pressure of summer and the air pressure of winter.

3.2.3. The discussion of air pressure variation:

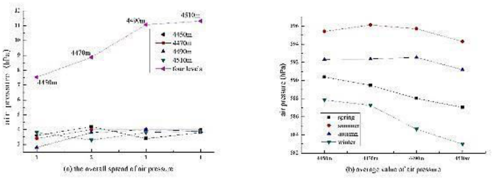


Fig.7: *The variation and average values of the atmosphere pressure in four levels at all seasons*

Through sorting out and analyzing statistics of air pressure in Fig 6, we can get the data in Fig 7. From Fig 7 (a), we can see seasonal change has great influence to air pressure of four levels, and the overall spread of air pressure all year round of four levels is distinctly above the overall spread of air pressure within four levels; higher altitude means more the overall periods of air pressure; the overall spread of air pressure in the level of 4510 m is distinctly above the level of 4450 m. The overall spread of air pressure within four levels in the main keeps in a horizontal line with little wave, as a result of influence of many factors, such as engineering arrangement inside well, gradient of rock temperature, ventilation work, mining and blasting work, and piston-wind conveyance. But, these influences are very little with equilibrium, coming near the surface air pressure of identical horizontal line. From Fig 7 (b), influenced by seasonal change, average values of air pressure variation of four levels represent different variation differences, that is, summer > autumn > spring >winter.

Some materials manifest that ranging from 2000 m to 5000 m of altitude level, air pressure and oxygen content of air decline as the altitude increases. At the same time, in the areas with similar latitude, on the condition of the same temperature, the date of air pressure depends on the data of altitude level. There are seasonal changes all year round, for instance, the period from December to March of next year is the time when the air pressure is the lowest in plateau; after May, the air pressure of plateau begins to increase and comes to top point in August. As the altitude level increases, the month of the highest air pressure moves forward. In the area of above 4000 m altitude, the time with the highest air pressure appears in August and September, and the time with the lowest air pressure appears in February and March. The mining area this article research belongs to typical continental plateau climate and its air pressure has distinctive characteristic seasonal change. All year round, the highest air pressure is in summer, and in the lower altitude area air pressure is higher with more oxygen content of air. The lowest air pressure is in winter, and in the higher altitude area air pressure is lower with less oxygen content of air. From this, the pressure supply range of miners should be determined on the basis of different seasons and average values of air pressure of four levels. That is, the pressure supply range of summer is little; the autumn and spring is less; the winter is least.

4. The research and judgment of the pressure supply range:

4.1. The building of mathematical model:

The aim of increasing pressure (or supplying oxygen) is to improve anoxic state and improve their labor efficiency when miners are working. In the view of anoxic environment at the altitude of 4000 m, the measurements of increasing pressure (or supplying oxygen) should be taken necessarily. Therefore, we summarize the foregoing research achievements, and build mathematical model of the pressure supply. The train of thought of modeling will comprehensively take the following influence factors into consideration: the altitude level in complete acclimatization stage; the equivalent altitude level after complete acclimatization stage; the altitude level used to distinguish plateau and plain in science (3000 m), that is, there will appear altitude reaction above 3000 m; the altitude level of mine operation area; the seasonal variation of air pressure inside well. We can get the following multivariate linear mode, that is

$$\begin{cases} y_i = (x_{1i} - x_{2i} + x_{3i}) - f(h_i) \\ f(h_i) = b_0 + b_1 h_i + b_2 h_i^2 + \cdots b_p h_i^p \end{cases} \quad (2)$$

In this formula, yi represents the pressure supply range, hPa; i=1,2,3,4 represent respectively spring, summer, autumn, winter; x_{1i} represents the air pressure used to judge the height in science, that is, the air pressure when altitude level is 3000 m, hPa; x_{2i} represents the air pressure environment index of equivalent altitude level corresponding the air pressure environment index of after acclimatization, hPa; x_{3i} represents the air pressure of altitude level after acclimatization, hPa; $f(hi)$ represents the variation range of air pressure inside well, hPa; hi represents the altitude level of four levels, m; b_0, b_1, b_2, …, b_p represents parameter to be estimated.

4.2. The range of the pressure supply:

According to the formula (2), the altitude level of complete acclimatization stage is 4000 m, and the air pressure there of seasonal change respectively are (615.80 hPa, 619.10 hPa, 617.00 hPa, 614.60 hPa); the equivalent altitude level corresponding to the capability of oxygen intake after complete acclimatization is 3000 m; the altitude level in science is 3000 m; the altitude of 4middle range respectively are 4450 m、4470 m、4490 m、4510 m, and Fig 7 shows the average value of air pressure change of four levels at four seasons. The result shows as Formula (3) and Fig 8 shows that mathematical equation of the pressure supply and the region of the pressure supply at four seasons in four levels.

$$\begin{cases} y_1 = x_{31} + 6.423\times10^{-6}\times h_1^2 - 717.651 \\ y_2 = x_{32} + 2.098\times10^{-6}\times h_2^2 - 637.495 \\ y_3 = x_{33} + 1.789\times10^{-6}\times h_3^2 - 628.027 \\ y_4 = x_{34} + 9.64\times10^{-6}\times h_4^2 - 779.167 \end{cases} \quad (3)$$

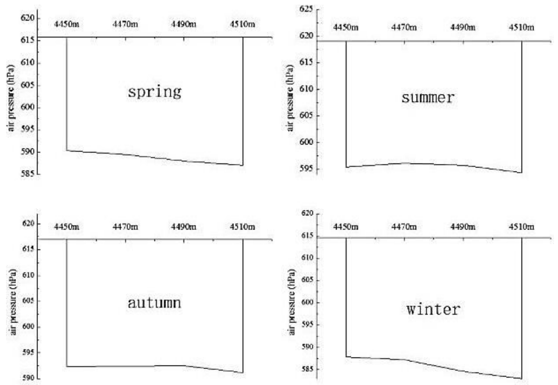


Fig.8: *Ranges of atmosphere pressure compensation in four levels at all seasons*

4.3. The discussion of the pressure supply:

When the standard atmospheric pressure of sea level is 1013.3 hPa, the content of oxygen is 0.298 kg/m^3, but the average value of air pressure of four levels is about 593 hPa, the content of oxygen is about 0.173 kg/m^3, this moment, the partial pressure of oxygen in alveolar is about 69.49 hPa, but the pressure difference of physiological alveolus breath is merely 6.67 hPa~26.66 hPa. The actual pressure difference from sea level to well is about 420 hPa, so that increasing the air pressure of well into sea level is very difficult to come true.

The altitude level of acclimatization test is 4000m, air pressure is 617 hPa, the content of oxygen is 0.181 kg/m^3, and the partial pressure of oxygen in alveolar after complete acclimatization is 82.5 hPa. This moment, the actual air pressure difference compared with well is about 24 hPa, so, if the air pressure of well operation is increased by about 24 hPa, or the content of oxygen is increased by about 0.008 kg/m^3, the partial pressure of oxygen in alveolar will be increased by about 13.01 hPa and the anoxic state under well for miners will be relieved.

From Fig 8, the following is the pressure supply range of four levels under well: (1) Spring, 25.41~28.76 hPa, average value, 27.07 hPa; (2) Summer, 23.69~24.8 hPa, average value, 23.71 hPa; (3) Autumn, 24.68 ~25.8 hPa, average value, 24.89 hPa; (4) Winter, 26.73~31.61 hPa, average value, 28.91 hPa.

The research manifests that low air pressure and lacking oxygen of plateau are the main causes of plateau reaction and low work capability, but the altitude level is not the only reason of sustaining anoxia severely. To improve the state of anoxia under well of miners, taking measurements of increasing pressure (or supplying oxygen) should take the degree of anoxia after acclimatization into consideration, thus, the range of increasing pressure (or supplying oxygen) could be reduced and the technological difficulties could be lowered.

5. Conclusion:

(1) At the altitude of 4000m, through complete acclimatization, breath and heart rate of miners these two indexes come near to the level of the plain contrast group; the index of the systolic blood pressure comes near to the level of the plain contrast group, but the diastolic blood pressure is above the level of the plain contrast group, which accords with the result that the organism adapts to the anoxic environment; the index of blood oxygen saturation at the beginning (86.40±6.19 %) increases to (90.42±3.43 %), and is close to the theoretical index parameter of oxygen intake at the altitude of 3000m.

(2) Affected by seasonal change and altitude level, the average value of overall period of air pressure variation of four levels is (9.70±1.81 hPa). Affected by the process of mine operation, the average value of overall period of air pressure variation of four levels is (3.73±0.22 hPa).

(3) After comprehensively thinking about the altitude level after complete acclimatization, the equivalent height, the height designated in science, altitude level range of mining area, and seasonal change these five factors, and building mathematical model of the pressure supply, we get the pressure supply range of four levels at different seasons for miners.

6. Acknowledgements:

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