Research Article

Test Verification of the Standard Compilation of “Energy-Saving Monitoring for Refrigeration Storage System” in Beijing

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In this paper, the feasibility and applicability of the test and evaluation methods for the temperature and energy consumption coefficient in the cold storage system are tested and verified which is specified in the Beijing local standard “Energy Conservation Monitoring of Refrigeration Storage.” It also summarizes and analyses the test verification results of the evaluation index of the location of measuring points of temperature in refrigeration storage, data-collecting time interval of temperature in refrigeration storage, energy efficiency coefficient of the refrigeration unit, and energy consumption coefficient of the refrigeration. The study work provides technical support for making the monitor and evaluation methods which applies to the standard.

1. Introduction

Nowadays, with the rapid development of refrigeration and logistics industry, the awareness of the food cold chain is stronger. Refrigeration storage has been the indispensable facility to the food industry. At the same time, with the rise of e-commerce and the implementation of national strategy “One belt and one road,” the business of high-end food import and export has achieved great growth and has created a new revenue plate of the cold chain system—large logistics cold storage [1]. According to relevant statistics, the total capacity of cold storage in China has exceeded 43 million tons by the end of 2017. In Beijing, the capital city of China, with the sustained and high-speed economic development, the demand for cold storage has also increased rapidly. It is reported that the capacity of cold storage in Beijing has reached 1574700 tons in 2018 and its capacity and volume rank first in north China [2]. At present, the total capacity of cold storage in China is increasing at an annual average rate of about 20%. Compared with the average capacity of 200 cubic meters per 1000 people in developed countries, the total capacity of cold storage in China has great potential for development [3]. From the view of cold storage energy consumption, the energy consumption level of the same type of cold storage in China is much higher than the average level in developed countries and the energy consumption is 26% and 46% higher than that of Britain and Japan [4].

In view of the rapid growth of cold storage and the high level of energy consumption, the relevant departments in Beijing have organized and compiled the local standard of “Energy-saving Monitoring of Cold Storage System” (hereinafter referred to as “Standard”). The Standard is applicable to the refrigeration which has been put into use and operated normally in Beijing area and provides a standard basis for energy saving monitoring of the refrigeration. In order to cooperate with the compilation of the Standard, the compilation team, taking into account the characteristics and actual situation of Beijing, has carried out feasibility and applicability verification of the monitoring and evaluation
methods in the Standard under the guidance of full investigation, analysis, experimental research, and experts, which provides technical basis for the scientific development of monitoring and evaluation methods in the Standard. The Standard has been compiled through extensive consultation.

This paper mainly summarizes and analyses the test and validation of the temperature and energy consumption coefficient in the cold storage as stipulated in the Standard, including the location of temperature measurement points in the cold storage, the time interval of temperature collection in the cold storage, the COP of refrigeration units, and the evaluation index of energy consumption coefficient in the refrigeration system. This part of the work is an important part of the preparation of the Standards, which provides technical support for the scientific development of monitoring and evaluation methods of the Standards. At the same time, the formulation of this evaluation method also fills in the blank of energy-saving monitoring and evaluation method for domestic cold chain logistics enterprises, which is of great significance to standardize and improve the overall operation level of the cold storage industry.

2. An Overview of the Test Contents

The test and verification work of the Standard mainly focuses on the following contents:

1. Different types of refrigerators with different storage capacities in Beijing were selected for monitoring and analysis, including ammonia refrigeration system and Freon refrigeration system, as well as civil cold storage and assembled cold storage. Verify the feasibility and applicability of the Standard.

2. The comparative test of the same cold storage was carried out according to different seasons, different recording time intervals, operating temperature, temperature distribution in the storage, collection time intervals, and so on, to verify the applicability of the “Standard” method, test conditions, test time, and other provisions.

3. The test data of all cold storage systems are classified and summarized, and the rationality of the indicators is verified by effective data calculation and coincidence analysis of monitoring indicators.

4. The research work includes the arrangement of temperature points in the cold storage, the test verification of the collection time interval, the test verification of COP of the refrigeration unit, and the evaluation index verification of the energy consumption coefficient of energy-saving monitoring of the refrigeration system.

3. Verification of the In-Storage Temperature Test

The “Standard” is to monitor the use of cold storage in operation. Due to the difference of the code and height of the items in the cold storage, the existing national standard GB/T30103.1-2013 “Test Method for Thermal Performance of Cold Storage Part 1: Temperature and Humidity Detection” stipulates the location of the measuring points “at least 3 points in each horizontal direction and at least 3 points in each vertical direction.” When the field test or the test conditions are not easy to meet or the operation is not convenient enough and the time interval of current standard data acquisition is different, factors such as compressor start-stop frequency, cold storage type, and test time should be considered comprehensively. This validation work has carried out targeted experimental verification on the location of measurement points and the acquisition time interval.

3.1. Location of Temperature Measuring Points in Cold Storage

In the cold storage, measuring points are arranged in horizontal and vertical directions. Finally, the average values of all measuring points are compared and analyzed with the average values of measuring points in the central region of each vertical direction: testing place #3, cold storage of a food company in Beijing; testing time: 17:20 on November 25, 2017, to 17:20 on November 26, 2017. The results are shown in Table 1.

Comparisons of test results at different time intervals and locations are shown in Figures 1–6.

In Table 1 and Figures 1–6, it can be seen that the working temperature, maximum temperature, and minimum temperature in the cold storage are basically the same and the deviation is not more than 0.3°C. The results show that the average values of all measure points in the height direction are in good agreement with those in the central region. Therefore, the “Standard” stipulates that the temperature measurement point in the height direction is within the range of 40%–60% of the net height of the cold storage, while retaining the requirement of “50 mm–100 mm from the horizontal end measurement point to the wall” in the original national standard, which improves the feasibility of field detection. The test position diagram is shown in Figure 7.

3.2. Time Interval of Data Collection

In the cold storage, measuring points are arranged in horizontal and vertical directions and temperature collection recorders with 5 min and 10 min collection intervals are arranged at the same measuring point. Finally, the average values of different collection intervals are compared and analyzed (including the comparison of different collection intervals for all measurement points and the comparison of different collection intervals for intermediate measurement points): testing place #3, cold storage of a food company in Beijing; testing time: 17:20 on November 25, 2017, to 17:20 on November 26, 2017. The results are shown in Tables 2 and 3.

Tables 2 and 3 show that the working temperature, the highest temperature, and the lowest temperature in the cold storage are basically the same after the stable operation of the cold storage. The maximum deviation is 0.26°C. It shows that the collection time interval of 5 minutes or 10
Table 1: Comparison of the temperature measurement position in storage.

(a)

| Collection interval (5 min) | Average value of all measuring points (°C) | Average value of central regional (°C) | Deviation (°C) |
|-----------------------------|------------------------------------------|---------------------------------------|---------------|
| Working temperature of cold storage | −17.41 | −17.36 | −0.05 |
| Highest temperature of cold storage | −14.87 | −14.87 | 0 |
| Lowest temperature of cold storage | −18.68 | −18.53 | −0.15 |

(b)

| Collection interval (10 min) | Average value of all measuring points (°C) | Average value of central regional (°C) | Deviation (°C) |
|-----------------------------|------------------------------------------|---------------------------------------|---------------|
| Working temperature of cold storage | −17.42 | −17.37 | −0.05 |
| Highest temperature of cold storage | −15.13 | −14.89 | −0.24 |
| Lowest temperature of cold storage | −18.62 | −18.47 | −0.15 |

Figure 1: Average temperature and midtemperature of measuring points at vertical position 1.

Figure 2: Average temperature and midtemperature of measuring points at vertical position 2.
minutes has little influence on the results. In the process of compiling this Standard, taking into account the factors such as the total test time, compressor operation mode, temperature fluctuation, and the time required for calculating the results, the time interval for temperature collection is stipulated as "not more than 10 minutes, the total test time is not less than 36 hours, and the temperature in the storage should be calculated by the continuous 24-hour data with the minimum temperature difference between the first and the last."

4. COP Test Validation of the Refrigeration Unit

In the process of compiling this standard, the energy consumption coefficient of the cold storage is determined, the refrigeration unit’s cooling demand is determined by referring to the calculation method of mechanical load in the design code of the cold storage, and the boundary value of refrigeration electric energy consumption (REC) is calculated based on the relationship with COP. Therefore, the

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**Figure 3:** Average temperature and midtemperature of measuring points at vertical position 3.

**Figure 4:** Average temperature and midtemperature of measuring points at vertical position 4.
COP value of the refrigeration unit is very important. In determining the value of COP, this standard adopts the method of combining theoretical calculation with experimental verification.

4.1. Theoretical Calculation of COP in Different Storage Temperature and Refrigerants. Considering the influence of different refrigerant types on COP, the compilation team investigated the use of refrigerant in the research process. Understanding that the United States and other developed countries have been looking beyond the HFC stage, natural refrigerants like NH₃ [5] and CO₂ [6, 7] have received unprecedented attention. Research on CO₂ and CO₂ and NH₃ cascade refrigeration is deepening. Besides, more and more practical applications are achieved. Now, there are more than 60 CO₂ systems in operation in the United States [8]. At present, NH₃ and R22 are the most commonly used refrigerants in the refrigeration system of our country. Among them, 80% of the refrigerators use ammonia as refrigerant and 20% of the refrigerators (mostly medium and small refrigerators) use R22 refrigerant.

According to the previous research results, there are four kinds of refrigerants commonly used in Beijing refrigerators: R22, R404 A, R134a, and R717. The theoretical COP of the four refrigerants at different evaporation and condensation temperatures is calculated by the compilation group, and the results are shown in Table 4.

Table 4 shows that COP of the same refrigerant ranges from 1.4 to 3.5 at different evaporation temperatures, while that of the same refrigerant is basically the same at different evaporation temperatures. For example, when the evaporation temperature is -35°C, the COP is 1.37 to 1.47. It can be seen that the theoretical values of COP for different refrigerants at the same evaporation and condensation temperatures are similar. Therefore, in the process of formulating the energy consumption coefficient, this Standard does not take into account the differences caused by different refrigerants. The reference values of COP determined are shown in Table 5.

4.2. COP Reference Value Test Verification. In order to further verify the COP reference value of the refrigeration unit in Table 5, the representative refrigerators were tested in winter and summer, by the compilation group. The sketch map of the location of the measuring points is shown in Figure 8. The seasonal deviation of COP test results and the deviation between COP test results and COP reference values are analyzed. The results are shown in Table 6.

Table 6 shows that the COP of different condensing units shows different trends in winter and summer. For air-cooled condensing units, COP of the system in summer is significantly lower than that in winter. For example, item no. 1 is an air-cooled condensing unit. The seasonal deviation of COP test results is 43.88%. For evaporation condensing units,
the seasonal deviations of COP test results of units with no. 2 and no. 4 refrigerators are 6.01% and 0.54%, respectively, and the seasonal variation of COP in the system is not obvious. The deviation between the summer test results and COP reference values is in the range of $-8.33\%$ to $7.78\%$. In practical use, the summer characteristics of the unit can better reflect its energy consumption level.

5. Test and Verification of the Energy Consumption Coefficient of Cold Storage

In the Standard, the energy consumption coefficient of the cold storage system is defined as “the daily energy consumption per cubic meter storage capacity when the cold storage system runs steadily.” To obtain this parameter, the total energy consumption (TEC) of the cold storage system is needed. The total energy consumption (TEC) of the refrigeration system is the sum of refrigeration power consumption (REC) and direct energy consumption (DEC). The refrigeration power consumption (REC) [9–11] is the energy consumption necessary for the refrigeration system within 24 hours, mainly for the refrigeration units and condensers.

| Table 2: Comparison of the results of different acquisition time intervals at all temperature measurement points in the cold storage. |
|---|---|---|---|
| Collection interval | Average value of all measuring points in 5 minutes (°C) | Average value of all measuring points in 10 minutes (°C) | Deviation (°C) |
| Working temperature of cold storage | −17.41 | −17.42 | 0.01 |
| Highest temperature of cold storage | −14.87 | −15.13 | 0.26 |
| Lowest temperature of cold storage | −18.68 | −18.62 | −0.06 |

| Table 3: Comparison of the results of different collection time intervals at the intermediate temperature measurement points in the cold storage. |
|---|---|---|---|
| Collection interval | Average value of all measuring points in 5 minutes (°C) | Average value of all measuring points in 10 minutes (°C) | Deviation (°C) |
| Working temperature of cold storage | −17.36 | −17.37 | 0.01 |
| Highest temperature of cold storage | −14.87 | −14.89 | 0.02 |
| Lowest temperature of cold storage | −18.53 | −18.47 | −0.06 |

| Table 4: COP calculations of four refrigerants at different storage temperatures. |
|---|---|---|---|---|---|
| Refrigerants | R22 | R134a | R404A | R717 | Average value |
| Design storage temperature (4°C); evaporation temperature (−6°C) | 3.52 | 3.31 | 3.06 | 3.93 | 3.46 |
| Design storage temperature (−5°C); evaporation temperature (−10°C) | 3.12 | 2.87 | 2.71 | 3.34 | 3.01 |
| Design storage temperature (−18°C); evaporation temperature (−28°C) | 1.64 | / | 1.85 | 1.74 | 1.74 |
| Design storage temperature (−25°C); evaporation temperature (−35°C) | 1.37 | / | 1.47 | 1.42 | 1.42 |

The abovementioned data are calculated according to the enthalpy and entropy of refrigerant under different evaporation temperature, suction pressure, condensation temperature, and hydraulic pressure. 2.R134a is not applicable in the low-temperature zone.

| Table 5: COP reference value for calculating energy consumption coefficient. |
|---|---|---|---|---|
| COP reference value | Design storage temperature (4°C); evaporation temperature (−6°C) | Design storage temperature (−5°C); evaporation temperature (−10°C) | Design storage temperature (−18°C); evaporation temperature (−28°C) | Design storage temperature (−25°C); evaporation temperature (−35°C) |
| 3.3 | 2.3 | 1.8 | 1.5 |

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Figure 8: Sketch map of measuring point position where 1: compressor; 2: testing sensor of inspiration temperature; 3: evaporator; 4: throttle valve; 5: temperature measurement sensor for liquid supply after liquid accumulator; 6: refrigerant flow testing instrument after liquid accumulator; 7: liquid accumulator; 8: temperature measurement sensor for liquid supply before liquid accumulator; 9: refrigerant flow testing instrument before liquid accumulator; and 10: condenser. Refrigerant flow rate and temperature test should be preferred at 8 and 9 locations. When this part does not meet the test conditions, choose the location of 5 and 6.
| Cold storage number | Project                                      | Refrigerant | Design of cold storage temperature (°C) | Types of condenser units | Test time | COP | Seasonal deviation of COP test results | Deviation from COP reference value |
|---------------------|----------------------------------------------|-------------|----------------------------------------|--------------------------|-----------|-----|---------------------------------------|----------------------------------|
| 1                   | A food co. ltd. of Beijing                   | R22         | −18°C                                  | Air-cooled condensing unit | Winter    | 2.83| 45.88%                               | 57.22%                           |
|                     |                                              |             |                                        |                          | Summer    | 1.94| 7.78%                                | 7.78%                            |
| 2                   | A food co. ltd. of Beijing                   | R22         | −18°C                                  | Evaporation condensing unit | Winter    | 1.94| 6.01%                                | 1.67%                            |
|                     |                                              |             |                                        |                          | Summer    | 1.83| 7.78%                                | 7.78%                            |
| 3                   | A food co. ltd. of Beijing                   | R22         | −18°C                                  | Air-cooled condensing unit | Summer    | 1.88| —                                    | 4.44%                            |
| 4                   | A food distribution company of Beijing        | R717        | −18°C                                  | Evaporation condensing unit | Winter    | 1.86| 0.54%                                | 3.33%                            |
|                     |                                              |             |                                        |                          | Summer    | 1.85| 2.78%                                | 2.78%                            |
| 5                   | A cold storage of food refrigeration plant of Beijing | R717        | −18°C                                  | Evaporation condensing unit | Summer    | 1.65| —                                    | −8.33%                           |
| 6                   | A by-product market co. ltd. of Beijing      | R717        | −18°C                                  | Evaporation condensing unit | Summer    | 1.50| —                                    | −16.67%                          |
| 7                   | A college pilot base in China                | R22         | 4°C                                    | Air-cooled condensing unit | Summer    | 3.43| —                                    | 3.94%                            |
(energy consumption necessary for the refrigeration system). Direct electric energy consumption (DEC) refers to the energy consumption of electrical components within 24 hours, including lighting, air cooler, defrosting, wind curtain, automatic control, auxiliary heating equipment, and circulating pump to meet the normal operation of the cold storage system of all ancillary equipment.

5.1. Calculation of the Energy Consumption Coefficient of the Cold Storage System

(1) The refrigeration power consumption (REC) of the cold storage system is calculated according to the following formula:

\[
REC = \frac{Q_s \times (T_e - T_{mrn})}{0.34 \times T_{mrn}},
\]

where \(REC\) is refrigeration power consumption (kWh), \(Q_s\) is the total refrigeration capacity in 24 hours (kWh), \(T_e\) is the average evaporation temperature (K), and \(T_{mrn}\) is the condensation temperature (K) (condensation temperature is a constant, 308.15 K)

(2) The direct power consumption (DEC) of the cold storage system is calculated according to the following formula:

\[
DEC = \sum_{i=1}^{n} E_i,
\]

where \(DEC\) is direct power consumption (kWh), \(E_i\) is the cumulative power of the \(i\)th meter in 24 hours (kWh), and \(n\) is the total number of direct energy consumption metering (watt-hour meters)

(3) The total refrigeration capacity \(Q_s\) within 24 hours is calculated according to the following formula:

\[
Q_s = \frac{G \rho (h_2 - h_1)}{3600},
\]

where \(Q_s\) is the 24 h total refrigeration capacity of the refrigeration system (kWh), \(G\) is the 24 h cumulative refrigerant flow (m³), \(\rho\) is the refrigerant density (kg/m³), \(h_1\) is the specific enthalpy of refrigerant (kJ/kg), and \(h_2\) is the specific enthalpy of refrigerant evaporation (kJ/kg). The average evaporation temperature is taken as the average suction temperature

(4) The total energy consumption TEC of the cold storage system for 24 hours is calculated according to the following formula:

\[
TEC = DEC + REC,
\]

(5) The energy consumption coefficient of the cold storage system is calculated according to the following formula:

\[
\varepsilon = \frac{TEC}{V},
\]

where \(\varepsilon\) is the daily power consumption per cubic meter (kWh/(m³·24 h)) (take the three significant digits after the decimal point) and \(V\) is the total storage capacity of the refrigerator (m³).

In order to obtain a reasonable evaluation index of energy consumption coefficient, the cooling requirement of the unit is determined by referring to the calculation method of mechanical load in the design code of refrigeration storage and the boundary value of refrigeration power consumption (REC) is calculated according to the relationship between COP and the unit. According to the experimental results, the direct energy consumption (DEC) is calculated. Finally, the total energy consumption (TEC) of the cold storage system is obtained, divided by the storage capacity, and the energy consumption coefficient is obtained. Refrigeration power consumption (REC) and unit COP are calculated by theory and verified by test. The index values are validated. The specified index values in the Standard are shown in Table 7.

5.2 Verification Results. In order to verify the rationality of the calculated energy consumption coefficient of Table 7 cold storage, the energy consumption coefficient of typical cold storage with different storage capacities and design temperature is tested. The results are detailed in Table 8.

In the process of testing, it is completely based on the test conditions, the layout of test points, the test methods, the calculation of results, and the evaluation of indicators stipulated in this Standard. Through testing, the measured energy consumption coefficients of different refrigerators are obtained, and finally, reliable test results are obtained to verify the applicability, operability, and rationality of the index formulation of this standard. Through the analysis of the unqualified items in Table 8, the main reasons for the unqualified items are as follows:

| Temperature of the cold storage | Coefficient of energy consumption (kW-h/(m³·24 h)) |
|---------------------------------|---------------------------------|
| +10°C to 0°C                    | 0.22                            | 0.18 | 0.16 |
| -1°C to 10°C                    | 0.32                            | 0.25 | 0.20 |
| -11°C to 20°C                   | 0.45                            | 0.33 | 0.27 |
| -21°C to 30°C                   | 0.66                            | 0.55 | 0.48 |
Table 8: Statistical table of energy consumption coefficient for different seasons and cold storages.

| Storage number | Design of storage temperature | Volume (m³) | Energy consumption coefficient in winter (kWh/(m³·24h)) | Energy consumption coefficient in summer (kWh/(m³·24h)) | Calculated value of energy consumption coefficient index (kWh/(m³·24h)) | Conclusion |
|----------------|-------------------------------|------------|------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------------------|------------|
| 1              | −18°C                         | 296        | 0.288                                                | 0.368                                                | 0.45                                                             | Qualified  |
| 2              | −18°C                         | 204        | /                                                   | 0.643                                                | 0.45                                                             | Unqualified|
| 3              | −18°C                         | 4847       | 0.289                                                | 0.362                                                | 0.33                                                             | Unqualified|
| 4              | −18°C                         | 131747     | 0.110                                                | 0.213                                                | 0.27                                                             | Qualified  |
| 5              | −18°C                         | 84602      | /                                                   | 0.191                                                | 0.27                                                             | Qualified  |
| 6              | Mix                           | 72320      | /                                                   | 0.379                                                | 0.27                                                             | Unqualified|
| 7              | 4°C                           | 775        | /                                                   | 0.109                                                | 0.22                                                             | Qualified  |

(1) Low-temperature reservoir no. 2 and no. 3 with smaller storage capacity do not meet the minimum requirements of the recommended values of design standards because of their poor enclosure structure, the test results are larger than the index values.

(2) The operation of the no. 6 refrigeration system is poor (COP is only 1.5), and the enclosure structure is a rice husk insulation structure. The test results are larger than the index value.

6. Conclusion

The experimental verification work described in this paper is an important part of the compilation of the Standard. Through a large number of researches, calculation, analysis, and experimental verification work, the compilation team summarized the energy consumption coefficient evaluation index, which provides a technical basis for the scientific development of the monitoring and evaluation method of the Standard. The energy consumption evaluation index proposed in this Standard will be widely applied to the cold storage systems of storage companies, catering management companies, food distribution companies, food refrigeration plants, and cold chain logistics companies in Beijing. The implementation of this standard can effectively standardize the energy consumption status of refrigeration enterprises in Beijing, and it is of great significance to ensure the energy-saving and efficient operation of the refrigeration system in Beijing.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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