Solar interference test for flame detectors based on natural lighting

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Abstract. In order to evaluate the anti-interference performance of the flame detector applied to the environment with possible solar interference, the feasibility of standardized test method for solar interference of flame detectors is researched in this paper. According to the characteristics such as structure, use place and installation mode of flame detector, the radiation model and illuminance model of solar interference are constructed. Through statistical analysis of photo-climatic data of regional representative cities, the severity level of the solar interference that reflecting national lighting conditions is summarized and classified. On this basis, data analysis of natural lighting resources of 8 typical cities in China is carried out. Combined with natural lighting test schemes, the feasibility of the solar interference test for flame detectors is analyzed, and relevant conclusions are drawn.

1. Introduction
In recent years, with the wide application of flame detectors in open or semi-open places such as tunnels, petrochemical plants, vehicles and ships, solar interference has become one of the main sources for false alarms[1][2]. The Chinese national standard GB 50116-2013 "Code for Design of Automatic Fire Alarm Systems" also clearly states that point-type flame detector is not suitable for places directly or indirectly exposed to sunlight or lamps. However, some products with better anti-interference performance (such as multi-band flame detector) can still be installed and used in places with complex ambient light, and play an important role in fire detection and alarm[3].

For flame detectors used in environments with possible solar interference, the monitoring angle of the detector is generally required to be horizontal or obliquely downward, and equipped with a sunshade to avoid direct sunlight (see figure 1). Therefore, for the solar interference of the flame detector, the direct irradiance of the horizontal plane should not be taken as the main reference, but the focus should be on the source of scattered radiation interference[4]. In rare cases that the sunshade does not function in direct sunlight, the sum of the direct radiation of vertical plane and scattering radiation should be taken as the reference value of the detector's solar interference.

Therefore, it is necessary to establish a solar interference irradiance model suitable for flame detector. On this basis, calculate and analyse the photo-climatic data of representative areas, so as to achieve the division of severity level for solar irradiance simulation test. Finally, the feasibility of solar interference test and the application scope of severity level are verified.
2. Flame detector solar interference model

2.1. Solar radiation model

The solar irradiance at the outer boundary of the atmosphere on a certain day of the year can be calculated by the following formula[5]:

\[ E_0 = E_{\text{ns0}} \times \left[ 1 + 0.034 \times \cos \left( 2 \pi \times \frac{N}{365} \right) \right] \tag{1} \]

Where \( E_{\text{ns0}} = 1367 \ \text{W/m}^2 \) is the reference constant for extra-terrestrial radiation provided by the World Meteorological Organization (WMO), and \( N \) is the cumulative number of days since January 1st. The daily maximum value of atmospheric transmittance \( k_m \) can be calculated by the following formula:

\[ k_m = E_m / E_0 \tag{2} \]

Where \( E_m \) is the daily maximum irradiance of total radiation (data from China Meteorological Data Network (CMDN)), and \( k_m \in (0, 1) \) can represent the clearness of the sky. According to the model proposed by Kreith & Kreider[6], we can get:

\[
\begin{align*}
\delta &= 23.45^\circ \times \sin \left[ \frac{360^\circ \times 284 + N}{365} \right] \\
\tau &= (12 - t) \times 15^\circ + (120^\circ - \Psi)
\end{align*}
\tag{3}
\]

Where \( \delta \) and \( \tau \) are the solar declination angle and the solar time angle, \( N \) is the cumulative number of days since January 1st, and \( t \) is the time when the daily maximum irradiance of total radiation occurs (data from CMDN). \( \Psi \) and \( \phi \) are the longitude and latitude values of the place under measurement. The altitude angle \( h \) of the sun can be calculated by the following formula:

\[ h = \arcsin \left[ \sin \delta \times \sin \phi + \cos \phi \times \cos \delta \times \cos \tau \right] \tag{4} \]

The value of atmospheric optical mass \( M \) is:

\[
\begin{align*}
M &= 1/\sin h \quad (h > 30^\circ) \\
M &= [1229 + (614 \times \sin h)]^{1/2} - 614 \times \sin h \quad (h \geq 30^\circ)
\end{align*}
\tag{5}
\]

Due to the lack of relevant data about the daily maximum value of the scattered radiation, the scattered radiation can only be estimated by the solar radiation model[7][8]. It is considered that the scattered radiation estimated at the time when daily maximum value of total radiation occurs is the daily maximum value of the scattered radiation.

\[
\begin{align*}
\left\{ \begin{array}{l}
k_s = 0.56 \times \left[ e^{-0.56 \times M} + e^{-0.96 \times M} \right] \times k_m \\
k_f = 0.271 - 0.2939 \times k_s
\end{array} \right.
\tag{6}
\]

Figure 1. Flame detectors installed in solar interference environment.
Where \( k_d \) and \( k_s \) are the estimated values of atmospheric transmittance of horizontal direct radiation and scattering radiation, and the daily maximum irradiance of scattering radiation can be calculated as follows:

\[
E_s = E_o \times k_s \tag{7}
\]

2.2. Illumination conversion model

Generally, the surface photo-climatic data is mainly based on solar radiation provided by the observation station. The measurement of solar radiation requires special equipment such as a radiometer. The purchase and maintenance costs are relatively high, which is not conducive to the popularity of flame detector manufacturers and product performance evaluation agencies. In addition, because the irradiance is not directly visual perception for human eyes, thus consider using illuminance as a measurement standard. The ratio of illuminance to irradiance of sunlight can be expressed by luminous efficacy \( K \)[9]:

\[
K = \frac{L}{E} = \frac{K_m}{\lambda} \int_{380}^{780} E_\lambda \times V_\lambda \ d\lambda \tag{8}
\]

Where \( L \) is the illuminance, \( E \) is the irradiance, \( K_m=683 \ \text{lm/W} \) is the light visual efficiency of the bright vision spectrum, \( E_\lambda \) and \( V_\lambda \) are the radiation amount and light visual efficiency under the wavelength \( \lambda \), respectively. According to the Muneer & Kinghorn Model[10][11], the total luminous efficacy \( K_a \) and the scattered luminous efficacy \( K_s \) can be calculated from the daily maximum value of atmospheric transmittance \( k_m \):

\[
\begin{aligned}
K_a &= 136.6 - 74.541k_m + 57.342k_m^2 \\
K_s &= 130.2 - 39.828k_m + 49.979k_m^2
\end{aligned} \tag{9}
\]

Therefore, the following formula can be used to calculate the daily maximum scattering illuminance \( L_s \) and the daily maximum vertical illuminance \( L_v \):

\[
\begin{aligned}
L_s &= K_s \times E_s \\
L_v &= K_v \times E_v + L_s
\end{aligned} \tag{10}
\]

Where \( E_s \) is the daily maximum irradiance of scattered radiation calculated using formula (7), and \( E_v \) is the daily maximum irradiance data of vertical radiation from CMDN.

3. Feasibility of solar interference test

3.1. Solar interference severity level

Based on the statistics of photo-climatic data in Shenyang, Shanghai, Guangzhou and Yuzhong in China from 2017 to 2019, and according to formula(1)–(7) in 2.1, the distribution of scattered radiation \( E_s \)(see figure 2a)) and the sum of vertical direct radiation and scattered radiation \( E_s + E_v \)(see figure 2b)) are calculated respectively.
Figure 2. Map of monthly changes of sunshine radiation in representative areas within two years.

According to the distribution of the estimated daily maximum scattered radiation, it can be seen that the radiation value is larger in winter, smaller in summer. The western and northern regions change more significantly with the seasons, and the eastern and southern regions have weak seasonal changes. Scattered radiation is also mostly higher than 70 W/m² at summer valleys, while the winter peak is basically around 300 W/m².

According to the distribution of the sum of vertical direct radiation and scattering radiation, it can be seen that the radiation value is not significantly affected by the monthly change, but there are certain regional differences. The radiation value of western city Yuzhong is higher, followed by
Shenyang in the north and Shanghai in the East, and Guangzhou in the south is generally smaller. The radiation values of the above selected places are basically distributed in the range of 500 W/m²~1000 W/m².

Through the above analysis results, the severity level of solar interference test for flame detector can be divided as follows:

Table 1. Severity level of solar interference test for flame detector.

| Severity level | Irradiance (W/m²) | Illumination (lx) | description | Application |
|----------------|-------------------|-------------------|-------------|-------------|
| 1              | 70                | 8000              | Lower limit of daily maximum of scattered radiation | Minimum requirements for environments where there may be solar radiation interference |
| 2              | 300               | 35000             | Upper limit of daily maximum of scattered radiation | Anti-interference requirements for non-direct solar radiation |
| 3              | 500               | 60000             | Lower limit of daily maximum of vertical direct radiation & scattered radiation | Minimum requirements for environments where direct solar radiation may be present |
| 4              | 1000              | 110000            | Upper limit of daily maximum of vertical direct radiation & scattered radiation | Requirements for anti-interference of vertical direct solar radiation |

3.2. natural lighting capacity

For performing solar interference test using natural lighting, collecting and simulating sunlight that meets the severity levels in any short period of time is essential.

For evaluating the maximum surface solar radiation that can be collected daily, the sum of horizontal direct solar radiation and scattered radiation is used as a criterion. According to the solar radiation model in 2.1, the daily maximum surface irradiance can be calculated by the following method:

\[ E_g = E_0 \times (k_d + k_s) \]  

(11)

Through formula (11), the daily maximum surface irradiance \( E_g \) is calculated based on photo-climatic of 8 representative cities from 2017.7 to 2019.6. The number of days in each month that can meet the corresponding severity level is calculated (see table 2).

Table 2. Number of days per month where daily maximum surface irradiance meets severity level.

| City & Severity level | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|-----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Beijing**           |     |     |     |     |     |     |     |     |     |     |     |     |
| 1                     | 31  | 28  | 31  | 30  | 31  | 30  | 31  | 31  | 30  | 31  | 30  | 31  |
| 2                     | 31  | 28  | 31  | 30  | 31  | 30  | 31  | 31  | 30  | 31  | 30  | 31  |
| 3                     | 30  | 27  | 30  | 28  | 30  | 29  | 29  | 30  | 28  | 28  | 28  | 30  |
| 4                     | 0   | 0   | 0   | 0   | 5   | 6   | 1   | 1   | 0   | 0   | 0   | 0   |
| **Shenyang**          |     |     |     |     |     |     |     |     |     |     |     |     |
| 1                     | 31  | 28  | 31  | 30  | 31  | 30  | 31  | 31  | 30  | 31  | 30  | 31  |
| 2                     | 31  | 28  | 31  | 30  | 31  | 30  | 31  | 31  | 30  | 31  | 30  | 31  |
| 3                     | 30  | 27  | 30  | 30  | 30  | 30  | 31  | 30  | 30  | 28  | 28  | 29  |
| 4                     | 0   | 0   | 0   | 7   | 12  | 12  | 7   | 4   | 1   | 0   | 0   | 0   |
| **Harbin**            |     |     |     |     |     |     |     |     |     |     |     |     |
| 1                     | 31  | 28  | 31  | 30  | 31  | 30  | 31  | 31  | 30  | 31  | 30  | 31  |
| 2                     | 31  | 28  | 31  | 30  | 31  | 30  | 31  | 31  | 30  | 31  | 30  | 31  |
| 3                     | 28  | 28  | 30  | 29  | 30  | 29  | 30  | 29  | 29  | 31  | 27  | 29  |
| 4                     | 0   | 0   | 1   | 3   | 1   | 4   | 15  | 1   | 0   | 1   | 0   | 0   |
From the statistical results in table 2, it shows that the daily maximum surface radiation of each city basically meet the requirements of severity level 1 and 2, most can meet the requirements of severity level 3, and very rarely can meet the requirements of severity level 4. In addition, since severity level 4 requires anti-interference of vertical direct solar radiation, which rarely occurs in the normal installation and use of flame detector. Therefore, it is not recommended to adopt the 4th severity level for the practical needs and test feasibility.

Furthermore, the daily maximum value of surface radiation calculated by formula (11) only reflects the theoretical value of the maximum sunlight that may be collected in different places. In actual test, the test time and lighting efficiency of test equipment will greatly affect the lighting intensity. Therefore, the theoretical feasibility of the test is analysed in this paper, and the actual test results for specific equipment and methods will continue to be deepened in the next step of research.

4. Conclusion
Based on the analysis of possible solar interference for flame detectors, the solar interference radiation model and the illuminance conversion model are constructed. According to the photo-climatic data of several cities in recent years, the distribution and range of the possible solar interference are analysed, and 4 severity levels are classified. By calculating the natural lighting capacity of 8 typical cities, the feasibility of the solar interference test of each severity level is analysed theoretically. The specific test equipment and methods will be study in the next.

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