Modelling Atmospheric Properties in Industrial Geodetic Measurements

S Mogilny¹, A Sholomitskii²

¹Prydniprovs'ka State Academy of Civil Engineering and Architecture, 24a, Chernyshevs'kogo St., Dnepr, 49600, Ukraine
²Department of Engineering Geodesy and Mine Surveying, Siberian State University of Geosystems and Technologies, 10 Plakhotnogo Str., Novosibirsk, 630108, Russian Federation

E-mail: mogilnysg@mail.ru, a.sholomitskj@gmail.com

Abstract. The article considers the questions of studying and modeling atmospheric properties in geodetic measurements on industrial objects near high-temperature aggregates. It is shown that atmospheric properties around such aggregates have significant differences, which influence geodetic measurements. The research was carried out on the basis of an industrial experiment on measuring atmospheric temperature field around a rotation kiln. The mathematical model of the air temperature field in the space around the kiln is divided into two zones: the first one – the space where the total station and sighting marks are positioned; the second one – the space from the shell surface to the distance ≤2.5m. The first zone temperature field is built on measurements made by inhausing thermocouple and interpolation between measurement points by Viner-Kolmogorov filter; the second zone field is built on measurements made on the shell surface by a pyrometer. The research showed that in the direction perpendicular to the aggregate axis the lines of equal temperatures are close to circles. The mathematical model of atmospheric temperatures allows to perform integration of differential equations of the sighting beam between any measurement points, to estimate the values of geodetic refraction, to choose more accurate measurement technology.

1. Introduction

The emergence of electronic total stations and trackers gave an impulse to the beginning of a new epoch in industrial geodesy, as they automated distance measurements and increased their accuracy. Geodetic methods became basic in construction, exploitation and monitoring of large-scale aggregates and installations, such as rolling mill machines, continuous casting machines, rotation kilns etc.

In industrial geodesy measurements, as a rule, are performed in restrictive conditions of factory workshops under the influence of high temperature air environment. The spatial temperature field during the measurements is not homogeneous; there are some particular spots of significantly high temperatures.

In such conditions the sighting beam suffers deviations, causing errors of angular measurements because of optical beam refraction [1 – 3]. Line lengths in industrial geodesy are not big, up to a couple of hundred meters, that’s why the distance error caused by refraction is significantly less than measurement error itself.
Refraction is defined by variable air density along the sighting beam. The main reason of variable air density is its temperature, which has rather big differences (sometimes up to hundreds of degrees) of particular parts of aggregate, e.g. the shell of rotation kiln. The temperature changes of the surrounding air happen mainly because of heat transfer and convection. Air heating because of thermal emission from the kiln is not significant [1].

In the works [3-6] shows that refraction influence in monitoring rotation kilns can lead to sufficient errors, which depend on measurement method. However the conclusions of the work [3] are based on a set of simplifications and suggestions, that’s why they require further substantiation.

The determination of refraction value in atmospheric layer near the surface is based on air temperature or its gradient determination along the sighting beam [7–11]. The measurements are performed, as a rule, only on the final beam points, and weather condition changes along the beam are taken into account based on some hypotheses. The work [9, p. 21] states, that in parallel air layers with the same density along the sighting beam the value of geodetic refraction depends only on the conditions on final points. We can show that this statement is wrong, and moreover, the derivation of refraction formula only on the basis of the Snell’s invariant is incorrect. The Snell’s invariant is derived from the Fermat’s principle, but not the equivalent to the latter [2].

2. Research objectives
There are proposals for taking geodesic refraction into account on the basis of direct determinations of the refractive index gradient of air from temperature measurements at different heights above the earth's surface [10,11]. In the present work, the problem is posed, how to obtain data for calculating the refraction values in angular measurements from the air temperature in the set of points in the space of geodetic measurements of a high-temperature aggregate.

3. Air temperature measurement
For determination of refraction value it is necessary to have an opportunity to calculate in every beam point the gradient vector of the temperature, for this purpose it is enough to build thermal space field, in which the measurements are performed. Because of significant thermal emission for the purpose of temperature measurement the authors constructed the device – inhausting digital thermocouple (figure1)

![Figure 1](image_url)

**Figure 1.** Scheme of inhausting thermocouple (1 – the layer reflecting infrared emission (foil); 2 – heat insulator; 3 – fan; 4 – digital thermocouples; 5 – air flow; 6 – revolving reflective mark).
The inhausting thermocouple was set on a tripod in the measurement point and stayed still during 2 minutes, for this time under the air flow (5) digital thermocouples (3) were meeting the temperature of the air, being pumped by the fan (3). The spatial positions of the inhausting thermocouple were being fixed with the help of revolving reflective mark (6) on which the measurements by electronic total station were being performed (figure 1b). In the result the following measurement data for every point were being registered in computer: point name; coordinates X,Y,Z and temperature T°C.

The measurements were performed on one of the kiln of OOO ISKITIM CEMENT plant (Iskitim town). The position of 63 measurement points is shown on figure 2.

![Figure 2](image2.png)

**Figure 2.** Position of air temperature measurement points in reference to the kiln body (the axes coordinates are expressed in meters).

The temperature on the surface of the kiln’s body is measured with infrared pyrometer GM550-50. Figure 3 shows the measurement results on the surfaces of the shell (line 1) and the bands (line 3). The differences in shell heating along its circle lead to the temperature shifts in lengthwise direction, that’s why in order to analyze the temperature there was performed the smoothing of the measured temperatures with sliding window (figure 3, line 2).

![Figure 3](image3.png)

**Figure 3.** Temperature on the kiln body surface: 1 – measured on the shell; 2 – smoothed measured on the shell; 3 – measured on the bands.

More vivid representation of the temperature distribution along the kiln body surface is shown on figure 4.
Figure 4. Temperature distribution on the kiln surface (°C).

4. Temperature field simulation

Using the obtained data one can build a digital model of the temperature field around the kiln. One should outline 2 zones in this model: the first one – the part of space within which in measuring the temperature the total station was set and the measurements themselves were performed by thermocouple; the second one – the spaces near the kiln body not far than \( r_{\text{max}} \).

Numerically the temperature field \( T_{\text{zone 1}} \) can be represented in view of the following function

\[
T_{\text{zone 1}} = \Phi_1(x, y, z, M),
\]

where \( x, y, z \) – point coordinates; \( M \) – set of points in the first zone, in which the air temperature is measured; \( \Phi_1 \) – the operator of interpolation on the set \( M \).

As interpolation operator were used the formulas of the filter of Viner-Kolmogorov [12]. Around the point with coordinates \( x_j, y_j, z_j \) was built the neighborhood \( S_i \), to which were chosen the points from the set \( M \), which met the condition

\[
\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \leq \varepsilon
\]

where \( \varepsilon \) – the neighborhood \( S_i \) radius; \( x_j, y_j, z_j \) the coordinates of the point in the neighborhood \( S_i \).

Covariance function \( K_{ij} \) between the temperature values in points \( i \) and \( j \) is accepted in linear view

\[
K_{ij} = a - \rho_{ij} / b,
\]

where \( \rho_{ij} \) – the distance between points \( i \) and \( j \) formula (2); \( a, b \) – parameters are chosen in such a way that interpolation does not lead to wild values. With such interpolation algorithm the isothermal surface is approximated by adjacent plane polygons.

The temperature in the first zone in point \( i \) with coordinates \( x_i, y_i, z_i \) is represented by the following function:

\[
T(x_i, y_i, z_i) = \frac{1}{m} \sum_{k=1}^{m} t_k + \begin{bmatrix} K_{1,1} & \cdots & K_{1,m} \\ \vdots & \ddots & \vdots \\ K_{m,1} & \cdots & K_{m,m} \end{bmatrix}^{-1} \begin{bmatrix} t_1 - \overline{t} \\ \vdots \\ t_m - \overline{t} \end{bmatrix},
\]

where \( m \) – number of points in neighborhood \( S_i \); \( \overline{t} \) – average temperature in neighborhood \( S_i \), calculated by formula

\[
\overline{t} = \frac{1}{m} \sum_{k=1}^{m} t_k.
\]

If to calculate the temperature values along the lines, which are parallel to cylinder surface of the kiln body and which are located on the equal distance from the kiln axis, then we get the graphs, shown on the figure 5.

The curves on the figure 4 are very close to each other, so it allows to suggest that in zone 2 the lines of equal temperatures in the section perpendicular to the kiln axis are close to concentric circles.
That’s why it is accepted that the temperature in this section along the direction of the shell radius from the kiln surface to the boundary of zone 1 changes exponentially according to the following equation

\[ T_x(y, z) = C_x e^{-\left(\frac{y^2 + z^2 - R}{\lambda_x}\right)}, \]  

(5)

where \( T_x \) – Characteristics of air temperature change in the section crossing the kiln axis in point with coordinate \( x \) and perpendicular to it; \( y, z \) – point coordinated in this section; \( R \) – radius of the kiln shell; \( C_x, \lambda_x \) – parameters for sectional plane with coordinate \( x \).

![Figure 5. Temperature along the lines, parallel to cylinder surface of the kiln body on the distance 5m from the axis on three different heights accordingly -2.5, -4.5 and -5.2m.](image)

The parameters \( C_x, \lambda_x \) are defined according to two conditions: on the shell surface the air temperature corresponds to the graph 2 (pic. 2), and on the boundary of the two zones – to the graph 1 (figure 5). The parameters are calculated by formulas

\[
\begin{align*}
C_x &= t_{x,2}; \\
\lambda_x &= \frac{r_{max}}{\ell n t_{x,2,2} - \ell n t_{x,1}}
\end{align*}
\]  

(6)

where \( t_{x,1}, t_{x,2} \) – the air temperature on the boundaries of, accordingly, the first and the second zone.

5. Conclusions

Thus, the field of the air temperatures is described by the following operator

\[
T(x, y, z) = \begin{cases} 
T_{zone \ 1} = \Phi_1(x, y, z, M) & \text{if } \sqrt{y^2 + z^2} > r_{max}; \\
T_{zone \ 2} = \Phi_2(x, y, z, M_1, M_2) & \text{otherwise}, 
\end{cases}
\]  

(7)

The functional (7) is continuous and allows numerical calculation of gradient in any point of temperature measurement point set, that’s why it can be included in solving differential equations, describing the optical sighting beam.

The offered building of atmospheric temperature field allows to study the influence of geodetic refraction for any most difficult conditions in installation and exploitation monitoring of high temperature industrial aggregates.
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