International Standard

ISO 6760-2

Optics and photonics — Test method for temperature coefficient of refractive index of optical glasses —

Part 2: Interferometric method

Optique et photonique — Méthode d'essai pour déterminer le coefficient de température de l'indice de réfraction des verres optiques —

Partie 2: Méthode interférométrique

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Foreword

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This document was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 3, *Optical materials and components*.

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Introduction

Optical glass is widely used in optical devices such as cameras, telescopes, and microscopes, and its refractive index is measured by the minimum deviation method (ISO 21395-1[4]) and the V-block refractometer method (ISO 21395-2[5]). Here, when designing an optical apparatus that requires high resolution, it is necessary to consider the temperature change of the refractive index of the optical glass in the usage environment. This document proposes a method for measuring the temperature coefficient of refractive index of optical glass with high accuracy.

Optics and photonics — Test method for temperature coefficient of refractive index of optical glasses —

Part 2: Interferometric method

1 Scope

This document specifies a test method for the temperature coefficient of refractive index of optical glass using interferometry. Temperature changes in optical glass lead to changes in the optical path length. The change in optical path length can be measured with an interferometer using the number of cycles of light/dark change of the interference stripe. This document defines a test method to measure the amount of change in the refractive index when the temperature of the specimen is changed continuously.

The intended temperature range for the specified measurement method is an arbitrary range.

The intended wavelength range for the specified measurement method is 365 nm to 1 014 nm.

The intended accuracy for the specified measurement method is within 1×10^{-6} K^{-1}.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
temperature coefficient of refractive index
ratio of refractive index change to temperature change at a selected wavelength

[SOURCE: ISO 9802:2022[3], 3.4.2.3, 3.4.2.4, modified — term and definition slightly reworded.]

3.2
temperature coefficient of absolute refractive index
$\Delta n_{abs}/\Delta T$
ratio of refractive index change in vacuum to temperature change at a selected wavelength

[SOURCE: ISO 9802:2022[3], 3.4.2.3, modified — term reworded.]

3.3
temperature coefficient of relative refractive index
$\Delta n_{rel}/\Delta T$
ratio of refractive index change at an air pressure of 1,013 25 × 10^5 Pa and a relative humidity of 0 % to temperature change at a selected wavelength

[SOURCE: ISO 9802:2022[3], 3.4.2.4, modified — term reworded and "0,101 33 × 10^6 Pa" and "0 % humidity" added.]

Note 1 to entry: This definition of $\Delta n_{rel}/\Delta T$ is for a specific pressure and humidity. $\Delta n_{rel}/\Delta T$ can be calculated for any other pressure and humidity by understanding the index of air in those conditions.

3.4
thermal chamber
chamber where the temperature of the specimen can be changed and/or maintained to a preset temperature

4 Principle

The temperature coefficient of refractive index is calculated in either Formula (1) or Formula (2) obtained by Annex C. The derivation of these formulae is described in Annex C. For a calculation method for obtaining the relative refractive index of glass at an arbitrary temperature and relative humidity, see Annex B.

$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{2} \times \frac{f \times \lambda}{L \times \Delta T} - \alpha_l \times n_{abs} \quad (1)$$

$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{2} \times \frac{f \times \lambda}{L \times \Delta T} - \alpha_l \times n_{rel} \quad (2)$$

where

$\frac{\Delta n_{abs}}{\Delta T}$	is the temperature coefficient of absolute refractive index of specimen (K^{-1});
$\frac{1}{2}$	is interferometer scale factor of double-path interferometers;
λ	is the wavelength of the refractive index temperature coefficient measurement (m);
L	is the measurement specimen length (m);
f	is the number of cycles of light/dark change of interference fringes associated with changes in optical path length of the specimen corresponding to ΔT;
ΔT	is the specimen temperature difference (K);
n_{abs}	is the absolute refractive index of the specimen;
n_{rel}	is the relative refractive index of the specimen;
α_l	is the linear expansion coefficient of the specimen (K^{-1}).

5 Measuring apparatus

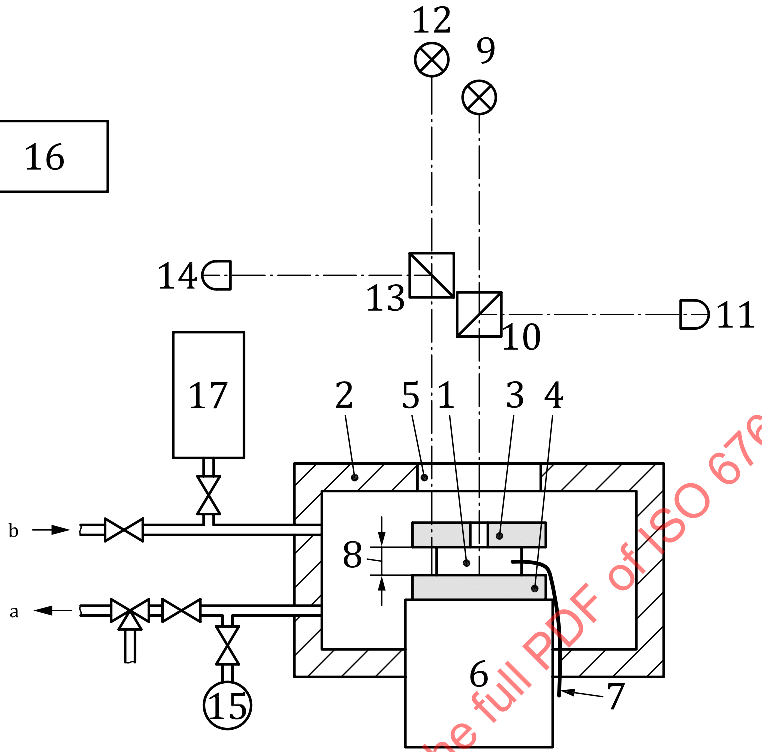
5.1 General

The measuring equipment shall be in accordance with the requirements in 5.2 to 5.9.

a) For measuring equipment, use the Fizeau-interference measurement principle in which the measured sample itself constitutes the interference space.

b) The resolution to read the number of cycles of light and dark changes in the interference space. The resolution shall be 1/10 cycle or less.

Figure 1 shows an example of a schematic diagram of the measuring equipment.



Key

1 specimen
2 thermal chamber shell
3 transmissive reference flat
4 reflective reference flat
5 window
6 heating/cooling unit
7 temperature sensor
8 mechanical length of the specimen
9 light source for optical path length change of the specimen measurement
10 beam splitter for optical path length change measurement
11 detector for optical path length change of the specimen measurement
12 light source for expansion measurement
13 beam splitter for expansion measurement
14 detector for expansion measurement
15 vacuum gauge
16 barometer
17 cushioning chamber (e.g. flexible plastic bag)
a Connection to vacuum pump.
b Dry air inlet.

Figure 1 — Example of a schematic drawing of a Fizeau-interferometric type of measurement equipment

5.2 Light sources

For change in optical path length of specimen light source and linear expansion coefficient light source, use a light source with sufficient intensity, monochromaticity and coherence to obtain interference fringes with the required precision. The wavelength for the measurement of the change in optical path length of specimen and linear expansion coefficient do not need to be the same.

NOTE 1 A sufficient light source, such as a laser, has to provide adequate illumination to enable accuracy, precision, and repeatability for the test.

NOTE 2 Examples of light sources are listed in ISO 7944:—[2], Table 1, Table 2 and Table 3.

5.3 Thermal chamber

The thermal chamber has a window for observing changes in the optical path length. Thermal chamber shall

a) have the ability to change the temperature of the specimen between the temperatures to be measured,

b) have the ability to maintain the temperature of the specimen within ±0,5 K,

c) have a thermometer to measure the temperature of the specimen with an accuracy of ±0,2 K or better,

d) have the ability to be filled with dry air at a relative humidity of 0 % or provide a vacuum with a residual pressure of less than 10 Pa to prevent condensation. When the inside of the thermal chamber is filled with dry air, the structure shall be such that the air pressure in the thermal chamber is the same as the atmospheric pressure around the container, and

e) have a window of the thermal chamber, which shall be made of quartz glass with a wedge angle of approximately 6 arc min (0,1°) on the opposite plane and polished on both sides.

NOTE Quartz glass is used because it has a wide wavelength range with a high transmittance, has a high durability against temperature changes, and is resistant to breakage.

5.4 Flat plates

Two flat plates, one is a transmission flat plate and the other is a reference flat plate, are used to measure the linear expansion coefficient of the specimen along with the change of the optical path length by using interference action. In the thermal chamber, the specimen is sandwiched between two plate's interference surfaces. Each interference surface shall be parallel with each interference surface of the specimen. Examples include point contact, line contact, surface contact, etc. An example of point contact is shown in Figure 2. The contact points of the specimen and the flat plate are on the same plane. The flat plate geometry is described in Annex F.

The required accuracies of the two flat plates are as follows:

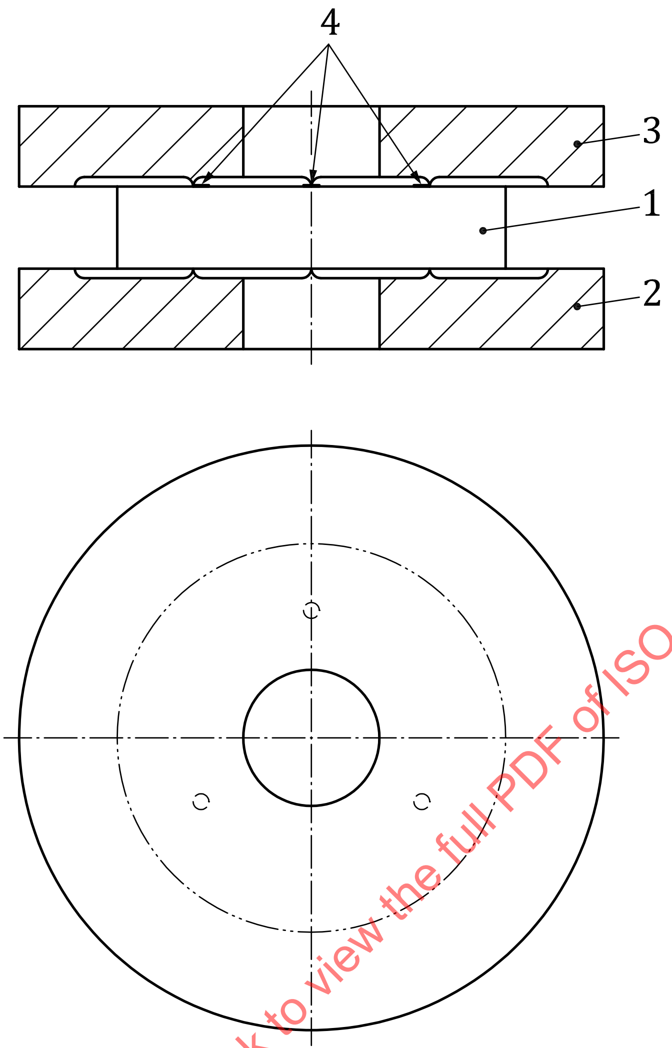
a) The transmission flat plate and reference flat plate shall be made of quartz glass or extremely low-expansion glass ceramics, where both sides of which have been polished with a wedge angle of approximately 6 arc min (0,1°).

b) The flatness of the surface used for the interference action shall be $\lambda/2$ or less (1/2 of the measurement wavelength of the linear expansion coefficient).

c) There shall be a hole in the centre of the transmission flat plate to secure the optical path for measurement of change in the optical path length of the specimen.

d) The back surface not involved in interference of the reference flat plate may be ground glass surface without polishing. In this case, the wedge angle of the reference flat plate is not required.

e) A suitable method should be used to ensure that reflections from the rear surface of the reference flat plate do not cause confusion with desired interference pattern. For example, there are sanding and donut-shaped processing by making a hole in the relevant position.



Key

1 specimen

2 transmissive reference flat plate

3 reflective reference flat plate

4 contact point

Figure 2 — Example of point contact between the specimen and 2 flat plates

5.5 Interferometer for optical path length change measurement

The interferometer used shall be able to measure the optical path length change of the specimen while changing the temperature of the specimen.

5.6 Interferometer for expansion measurement

The interferometer used shall be able to measure the length change of the specimen while changing the temperature of the specimen.

5.7 Detectors

The detector used shall be able to detect bright to dark changes due to interference of reflected light from the specimen, and bright to dark changes due to interference of reflected light from 2 flat plates.

5.8 Temperature sensor

The temperature sensor used to measure the temperature of specimen shall have a measurement accuracy within 0,2 K or less.

Additionally, when the inside of the thermal chamber is filled with dry air, the temperature in the space between the two flat plates should be measured by using a second thermometer which also has a measurement accuracy within 0,2 K or less. However, if there is no difference between the temperature of the space between the two flat plates and the temperature of the specimen, the temperature of the specimen may be taken as the temperature between the flat plates. The temperature sensor, which measures the temperature of the specimen, shall be in contact with the specimen to avoid a break in heat transfer due to vacuum.

5.9 Barometer

If dry air is filled in the thermal chamber, a barometer with a measurement accuracy of 0,05 kPa or better shall be used. If the structure is such that the air pressure in the thermal chamber is the same as the air pressure around the container, a barometer independent of the thermal chamber may be used. In a vacuum the barometer shall be suitable to guarantee that the air pressure is below 10 Pa.

6 Measurement specimen

Measurement specimen shall follow the requirements below:

a) Specimen materials shall be annealed sufficiently to ensure that the phase difference due to birefringence is not more than 5 nm per cm. Materials containing visible defects, such as striae, bubbles, or inclusions shall not be used. Materials used should contain striae of grade SW30 or less and bubbles and inclusions of grade IC10 and IN30 respectively or less.

b) The test specimen shall have two parallel, flat polished surfaces. The dimensions and shape of the parallel plate should be 20 mm to 25 mm in diameter and approximately 5 mm in sample length, considering the amount of change in the optical path length to be measured, the temperature distribution in the measurement sample, and the coherence of the measurement light.

NOTE A longer optical path length is better for measurement, and a shorter sample length is better for temperature distribution. The sample length that satisfies both the required optical path length and the temperature distribution is approximately 5 mm.

c) The parallelism between the facing plane shall be 10 arc sec (approx. 0,003°) or less, whereas the flatness shall be $\lambda/2$ (1/2 of the wavelength of light source for optical path length change measurement) or less.

d) Absolute refractive index $n_{abs}(T_0)$ or relative refractive index $n_{rel}(T_0)$ at reference temperature T_0 shall be known with an accuracy of 1×10^{-4} or less. Because the accuracy of temperature coefficient of refractive index is highly dependent on the accuracy of expansion coefficient, the accuracy of refractive index of 1×10^{-4} or less is sufficient. T_0 shall be any temperature within the range of 23 °C ± 2 °C.

NOTE Since it is difficult to measure absolute refractive index $n_{abs}(T_0)$ or relative refractive index $n_{rel}(T_0)$ with the same specimen as for temperature coefficient of refractive index, for example, produce a specimen for refractive index measurement from the glass material part adjacent to the specimen, and the relative refractive index $n_{rel}(T_0)$ at the reference temperature T_0 can be measured in accordance with ISO 21395-1[4] or ISO 21395-2[5].

7 Measurement procedure

The measurement procedure is as follows:

a) Sandwich the specimen between two flat plates (see Figure 2), place the specimen in the interferometric type measuring equipment (see Figure 1).

b) Fill the inside of the thermal chamber with dry air at a relative humidity of 0 % or a vacuum of not more than 10 Pa.

c) Lower the specimen temperature to -50 °C or less and raise the temperature to at least 90 °C or more. It is also allowed to start the measurement after raising the specimen temperature to 90 °C at least and lowering the temperature to -50 °C or less. This shall be done at the rate at which the temperature distribution within the specimen is within 1,0 K. The speed at which the temperature distribution in the specimen is within 1,0 K depends on the measuring instrument and should be confirmed in a preliminary test. Typical heating rate and temperature distribution are described in Annex G.

d) During the measurement (in either direction of the temperature change), continuously record the specimen temperature and the number of cycles, f, that the interference stripe changes from light to dark. Sensors can be used for recording. See Annex D for sensor specifications. The resolution of the light/dark change readings for the interference stripes shall be 1/10 cycle or less. At the same time as c), continuously measure the number of cycles, f_{α}, of the light/dark change of the interference stripes of the interference space between the two flat plates. In this case, the reading resolution of the light/dark change of interference stripes shall be 1/10 cycle or less. See Annex E for an example of the procedure for determining the amount of number of cycles of light/dark change of interference shift between two temperatures.

e) If the inside of the thermal chamber is filled with dry air having a relative humidity of 0 %, continuously record the temperature of the dry air in the space between the flat plates at the same time as c) and d).

f) If the inside of the thermal chamber is filled with dry air having a relative humidity of 0 %, measure and record the air pressure in the thermal chamber at the same time as c) and d). If the structure is such that the air pressure in the thermal chamber is the same as the air pressure around the container, the measurement of the atmospheric pressure in the vicinity of the chamber may be used instead.

8 Calculation

8.1 Temperature coefficient of absolute refractive index

Calculate the temperature coefficient of the absolute refractive index in accordance with Formula (3) using Formula (C.5). For a formula describing the temperature coefficient of the absolute refractive index as a function of temperature and wavelength, see ISO 6760-1[1]:

$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{2} \times \frac{\lambda}{L} \times \frac{f}{\Delta T} - \alpha_1 \times n_{abs}(T_0) \tag{3}$$

where

$\frac{\Delta n_{abs}}{\Delta T}$	is the temperature coefficient (K^{-1}) of absolute refractive index of the specimen;
$\frac{1}{2}$	is interferometer scale factor of double-path interferometers;
λ	is the refractive index temperature coefficient measurement wavelength in vacuum (m);
L	is the measurement specimen length (m);
f	is the number of cycles of light/dark change in interference fringes associated with changes in optical path length of specimen corresponding to ΔT;
ΔT	is the specimen temperature difference (K);
$n_{abs}(T_0)$	is the absolute refractive index of the specimen at ambient temperature T_0;
T_0	is the reference temperature at which the refractive index of the specimen is measured, 23 °C ± 2 °C;
α_1	is the linear expansion coefficient of specimen (K^{-1}).

NOTE 1 The temperatures for calculation are arbitrary. When the temperature change ΔT of the specimen is 20 K, calculate the temperature coefficient of the relative refractive index in the 6 temperature ranges: -40 °C to -20 °C, -20 °C to 0 °C, 0 °C to 20 °C, 20 °C to 40 °C, 40 °C to 60 °C and 60 °C to 80 °C.

NOTE 2 In this document, all temperature symbols are represented by "T". The original symbol for temperature in ISO 80000-5[6] is "t" or "ϑ" for temperature in Celsius degrees, and "T" for absolute temperature.

8.2 Linear expansion coefficient of specimen

The linear expansion coefficient of the specimen is calculated as follows:

a) If the inside of the thermal chamber is vacuum, calculate using Formula (4).

$$\alpha_1 = \frac{1}{2} \times \frac{f_\alpha \times \lambda_\alpha}{L \times \Delta T} \quad (4)$$

b) If the inside of the thermal chamber is filled with dry air at 0 % relative humidity, calculate using Formula (5).

The formula for calculating the refractive index of air at any temperature T and air pressure p and the temperature coefficient of refractive index of air are given in Annex A.

$$\alpha_1 = \frac{1}{2} \times \frac{f_\alpha \times \lambda_\alpha}{L \times \Delta T_\alpha \times n_{air}(T,p)} - \frac{\Delta n_{air}(p)}{\Delta T} \times \frac{1}{n_{air}(T,p)} \quad (5)$$

where

α_1	is the linear expansion coefficient of specimen (K^{-1});
$\frac{1}{2}$	is interferometer scale factor of double-path interferometers;
f_α	is the number of cycles of the light/dark change of interference stripes in the interference space between two flat plates corresponding to ΔT_α;
λ_α	is the linear expansion coefficient measurement wavelength (m);
L	is the specimen length (m);
ΔT_α	is the change in the temperature in the interference space between two flat plates (K);
$n_{air}(T, p)$	is the refractive index of air at temperature T and air pressure p in the interference space between two flat plates;
T	is the centre value (°C) of the temperature range for calculation of the temperature coefficient of refractive index;
p	is the mean air pressure (Pa) in the thermal chamber during measurement of the temperature range for calculation of the temperature coefficient of refractive index;
$\frac{\Delta n_{air}(p)}{\Delta T}$	is the temperature coefficient of refractive index of air at air pressure p in the temperature range for calculation of the temperature coefficient of refractive index (K^{-1}).

8.3 Temperature coefficient of relative refractive index

Calculate the temperature coefficient of the relative refractive index by Formula (6) using the temperature coefficient of the absolute refractive index determined in clause 8.1. The temperatures for calculation are arbitrary. When the temperature change ΔT of the specimen is 20 K, calculate the temperature coefficient of the relative refractive index in the 6 temperature ranges: −40 °C to −20 °C, −20 °C to 0 °C, 0 °C to 20 °C, 20 °C to 40 °C, 40 °C to 60 °C and 60 °C to 80 °C. The temperature coefficients of the refractive index in air are listed in Table 1 for each wavelength. The absolute refractive index of the specimen at T_1 and T_2 shall be calculated according to Annex B. Derivation and verification of $\Delta n_{rel}/\Delta T$, see ISO 6760-1[1].

$$\frac{\Delta n_{rel}}{\Delta T} = \frac{\Delta n_{abs}}{\Delta T} - \frac{n_{abs}(T_1) + n_{abs}(T_2)}{2} \times \frac{\Delta n_{air}}{\Delta T} \quad (6)$$

where

$\frac{\Delta n_{rel}}{\Delta T}$ is the temperature coefficient of the relative refractive index of the specimen (K^{-1});

$\frac{\Delta n_{abs}}{\Delta T}$ is the temperature coefficient of the absolute refractive index of the specimen (K^{-1});

$\frac{\Delta n_{air}}{\Delta T}$ is the temperature coefficient of the refractive index of air (K^{-1}).

Table 1 — Temperature coefficient of refractive index of air (air pressure 1,013 25 × 10^5 Pa, relative humidity 0 %)

Spectral line	Wavelength nm	$\Delta n_{air}/\Delta T$ (10^{-6} K^{-1}) in the temperature range of					
		−40 °C to 20 °C	−20 °C to 0 °C	0 °C to 20 °C	20 °C to 40 °C	40 °C to 60 °C	60 °C to 80 °C
i	365,01	−1,40	−1,19	−1,03	−0,90	−0,79	−0,70
h	404,66	−1,38	−1,18	−1,02	−0,89	−0,78	−0,69
g	435,83	−1,38	−1,17	−1,01	−0,89	−0,78	−0,69
F'	479,99	−1,37	−1,17	−1,01	−0,88	−0,77	−0,69
F	486,13	−1,37	−1,17	−1,01	−0,88	−0,77	−0,69
e	546,07	−1,36	−1,16	−1,00	−0,88	−0,77	−0,68
d	587,56	−1,36	−1,16	−1,00	−0,87	−0,77	−0,68
He-Ne	632,8	−1,35	−1,16	−1,00	−0,87	−0,77	−0,68
C'	643,85	−1,35	−1,16	−1,00	−0,87	−0,77	−0,68
C	656,27	−1,35	−1,15	−1,00	−0,87	−0,77	−0,68
r	706,52	−1,35	−1,15	−1,00	−0,87	−0,76	−0,68
t	1 013,98	−1,34	−1,15	−0,99	−0,86	−0,76	−0,67

9 How to express the temperature coefficient of refractive index

The temperature coefficient of the absolute refractive index and of the relative refractive index of the values calculated in 8.1 to 8.3 shall be rounded to 1 decimal place in units of 10^{-6} K^{-1}. An example is shown in Table 2.

Table 2 — Example of how to express the temperature coefficient of refractive index

Spectral line	Wavelength nm	$\Delta n_{abs}/\Delta T$ (10^{-6} K^{-1}) in the temperature range of					
		−40 °C to 20 °C	−20 °C to 0 °C	0 °C to 20 °C	20 °C to 40 °C	40 °C to 60 °C	60 °C to 80 °C
d	587,56	3,8	3,8	3,9	4,0	4,1	4,2

10 Test report

The test report should include the following information:

a) method used (interferometric);

b) a reference to this document, e.g. ISO 6760-2:2024;

c) melt number, lot number or alternative means of indicating the specific test sample;

d) date of measurement;

e) the temperature coefficient of absolute refractive index obtained by calculation;

f) the temperature coefficient of relative refractive index obtained by calculation;

g) any deviations from the procedure;

h) any unusual features observed.

Annex A
(informative)

Formula for calculating the refractive index of air

The refractive index of air can be obtained from Formulae (A.1) to (A.7) based on the formulae shown in References [2] and [3]. Using Formulae (A.1) to (A.7), the refractive index of air can be determined with the precision required for this specification in the wavelength range of 300 nm to 1,700 nm, temperature range of −40 °C to 100 °C, air pressure range of 10 kPa to 140 kPa, and relative humidity range of 0 % to 100 %.

NOTE 1 The formula shown in Reference [2] is the Edlén formula.

NOTE 2 The formula shown in Reference [1] describes the term related to the relative humidity in a non-temperature-dependent format. Formulae (A.1) to (A.7) represent modifications to the term related to relative humidity of the shown in Reference [1] to improve calculation accuracy over a wide temperature range.

NOTE 3 This value can also be calculated using the Ciddor formula as per Reference [3].

$$n_{\mathrm{air}} = n(T,p,h) - 10^{-10} \times \frac{292{,}75}{T + 273{,}15} \times (3{,}734\,5 - 0{,}040\,1 \times S) \times p_{\mathrm{V}} \quad \text{(A.1)}$$

$$n(T,p,h) = 1 + \frac{p(n_{\mathrm{s}} - 1)X}{D} \quad \text{(A.2)}$$

$$n_{\mathrm{s}} = 1 + 10^{-8}\left(A + \frac{B}{130 - S} + \frac{C}{38{,}9 - S}\right) \quad \text{(A.3)}$$

$$X = \frac{1 + 10^{-8}(E - F \times T)p}{1 + G \times T} \quad \text{(A.4)}$$

$$S = \frac{1}{\lambda^2} \quad \text{(A.5)}$$

$$p_{\mathrm{v}} = h \times p_{\mathrm{sv}} \quad \text{(A.6)}$$

$$p_{\mathrm{sv}} = 6{,}112 \times 10^{2} \times \exp\left(\frac{17{,}62 \times T}{243{,}12 + T}\right) \quad \text{(A.7)}$$

where

n_{air}	is refractive index of air at temperature *T*, air pressure *p*, and relative humidity $(p_{\mathrm{V}}/p_{\mathrm{SV}})$ %;
p_{V}	is vapor partial pressure (Pa);
$n(T, p, h)$	is refractive index of air at temperature *T*, air pressure is *p*, and relative humidity *h*;
T	is temperature (°C);
p	is air pressure (Pa);
S	is $1/\lambda^2$ (μm^{-2});
λ	is wavelength of light in vacuum (μm);

h is the relative humidity of air (%);

p_{sv} is the saturated water vapor pressure of air at temperature T (Pa);

A = 8 342,54

B = 2 406 147

C = 15 998

D = 96 095,43

E = 0,601

F = 0,009 72

G = 0,003 661

As an example, Table A.1 shows the refractive index values of air in the representative spectral lines calculated by the actual values in these formulae.

Table A.1 — Refractive index of air (air pressure 1,013 25 × 10^5 Pa, relative humidity 0 %)

Spectral wavelength nm	Temperature						
	−40 °C	−20 °C	0 °C	20 °C	40 °C	60 °C	80 °C
i 365,01	1,000 352 35	1,000 324 45	1,000 300 63	1,000 280 07	1,000 262 13	1,000 246 34	1,000 232 35
h 404,66	1,000 349 34	1,000 321 68	1,000 298 07	1,000 277 68	1,000 259 89	1,000 244 24	1,000 230 36
g 435,83	1,000 347 57	1,000 320 05	1,000 296 55	1,000 276 27	1,000 258 57	1,000 243 00	1,000 229 19
F' 479,99	1,000 345 66	1,000 318 29	1,000 294 92	1,000 274 75	1,000 257 15	1,000 241 67	1,000 227 93
F 486,13	1,000 345 44	1,000 318 08	1,000 294 73	1,000 274 57	1,000 256 98	1,000 241 51	1,000 227 79
e 546,07	1,000 343 66	1,000 316 44	1,000 293 22	1,000 273 16	1,000 255 66	1,000 240 27	1,000 226 61
d 587,56	1,000 342 74	1,000 315 60	1,000 292 43	1,000 272 43	1,000 254 98	1,000 239 63	1,000 226 01
He-Ne 632,8	1,000 341 95	1,000 314 87	1,000 291 76	1,000 271 80	1,000 254 39	1,000 239 07	1,000 225 49
C' 643,85	1,000 341 78	1,000 314 72	1,000 291 61	1,000 271 67	1,000 254 27	1,000 238 95	1,000 225 38
C 656,27	1,000 341 60	1,000 314 55	1,000 291 46	1,000 271 52	1,000 254 13	1,000 238 83	1,000 225 26
r 706,52	1,000 340 98	1,000 313 97	1,000 290 93	1,000 271 03	1,000 253 67	1,000 238 39	1,000 224 85
t 1 013,98	1,000 338 97	1,000 312 13	1,000 289 22	1,000 269 44	1,000 252 18	1,000 236 99	1,000 223 53

Annex B
(normative)

Calculation of absolute refractive index of specimen at a given temperature using the temperature coefficient of refractive index

B.1 Formula for calculating the refractive index

The absolute refractive index $n_{abs}(T)$ of specimen at a temperature T is calculated from Formula (B.1) or Formula (B.2) depending on whether the known refractive index at the reference temperature, T_0 of the specimen is the absolute refractive index $n_{abs}(T_0)$ or relative refractive index $n_{rel}(T_0)$. When the (B.2) is used, the refractive index $n_{air}(T_0)$ at the reference temperature, T_0, can be calculated from Formulae (A.1) to (A.7) in Annex A.

$$n_{abs}(T) = n_{abs}(T_0) + \Delta n_{abs} \tag{B.1}$$

$$n_{abs}(T) = n_{rel}(T_0) \times n_{air}(T_0) + \Delta n_{abs} \tag{B.2}$$

where

$n_{abs}(T)$	is the absolute refractive index of the specimen at temperature T;
$n_{abs}(T_0)$	is the absolute refractive index of the specimen at reference temperature T_0;
$n_{rel}(T_0)$	is the relative refractive index of the specimen at reference temperature T_0;
$n_{air}(T_0)$	is the refractive index of air at reference temperature T_0;
Δn_{abs}	is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature.

Since the temperature coefficient of the refractive index varies depending on the temperature range, calculate Δn_{abs} in Formula (B.1) or Formula (B.2) using either of Formulae (B.3) to (B.8) depending on the value of T.

In this specification, the reference temperature T_0 is 23 °C ± 2 °C.

B.2 Formula for calculation of refractive index change at a given temperature, T

a) Calculation formula when −40 °C ≤ T < −20 °C

$$\Delta n_{abs,T_0,T} = (20 - T_0) \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{20,40} - 20 \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{0,20} - 20 \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{-20,0} + (T + 20) \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{-40,-20} \tag{B.3}$$

where

$\Delta n_{\mathrm{abs},T_0,T}$	is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature;
T_0	is the reference temperature (23 °C ± 2 °C);
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{20,40}$	is the temperature coefficient of absolute refractive index at 20 °C to 40 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{0,20}$	is the temperature coefficient of absolute refractive index at 0 °C to 20 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{-20,0}$	is the temperature coefficient of absolute refractive index at −20 °C to 0 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{-40,-20}$	is the temperature coefficient of absolute refractive index at −40 °C to 20 °C;
T	is an arbitrary temperature (°C).

b) Calculation formula when −20 °C ≤ T < 0 °C

$$\Delta n_{\mathrm{abs},T_0,T} = (20 - T_0) \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{20,40} - 20 \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{0,20} + T \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{-20,0} \quad \text{(B.4)}$$

where

$\Delta n_{\mathrm{abs},T_0,T}$	is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature;
T_0	is the reference temperature (23 °C ± 2 °C);
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{20,40}$	is the temperature coefficient of absolute refractive index at 20 °C to 40 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{20,40}$	is the temperature coefficient of absolute refractive index at 0 °C to 20 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{-20,0}$	is the temperature coefficient of absolute refractive index at −20 °C to 0 °C.

c) Calculation formula when 0 °C ≤ T < 20 °C

$$\Delta n_{\mathrm{abs},T_0,T} = (20 - T_0) \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{20,40} - (T - 20) \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{0,20} \quad \text{(B.5)}$$

where

$\Delta n_{\mathrm{abs},T_0,T}$	is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature;
T_0	is the reference temperature (23 °C ± 2 °C);
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{20,40}$	is the temperature coefficient of absolute refractive index at 20 °C to 40 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T}\right)_{0,20}$	is the temperature coefficient of absolute refractive index at 0 °C to 20 °C;

T is an arbitrary temperature (°C).

d) Calculation formula when 20 °C ≤ T < 40 °C

$$\Delta n_{abs,T_0,T} = (T - T_0) \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{20,40} \tag{B.6}$$

where

$\Delta n_{abs,T_0,T}$ is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature;

T_0 is the reference temperature (23 °C ± 2 °C);

$\left(\frac{\Delta n_{abs}}{\Delta T}\right)_{20,40}$ is the temperature coefficient of absolute refractive index at 20 °C to 40 °C;

T is an arbitrary temperature (°C).

e) Calculation formula when 40 °C ≤ T < 60 °C

$$\Delta n_{abs,T_0,T} = (40 - T_0) \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{20,40} + (T - 40) \times \left(\frac{\Delta n_{abs}}{\Delta T}\right)_{40,60} \tag{B.7}$$

where

$\Delta n_{abs,T_0,T}$ is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature;

T_0 is the reference temperature (23 °C ± 2 °C);

$\left(\frac{\Delta n_{abs}}{\Delta T}\right)_{20,40}$ is the temperature coefficient of absolute refractive index at 20 °C to 40 °C;

$\left(\frac{\Delta n_{abs}}{\Delta T}\right)_{40,60}$ is the temperature coefficient of absolute refractive index at 40 °C to 60 °C;

T is an arbitrary temperature (°C).

f) Calculation formula when 60 °C ≤ T < 80 °C

$$\Delta n_{\mathrm{abs},T_0,T} = (40 - T_0) \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T} \right)_{20,40} + 20 \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T} \right)_{40,60} + (T - 60) \times \left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T} \right)_{60,80} \quad \text{(B.8)}$$

where

$\Delta n_{\mathrm{abs},T_0,T}$	is the change in refractive index determined from the temperature coefficient of absolute refractive index and change in temperature;
T_0	is the reference temperature (23 °C ± 2 °C);
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T} \right)_{20,40}$	is the temperature coefficient of absolute refractive index at 20 °C to 40 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T} \right)_{40,60}$	is the temperature coefficient of absolute refractive index at 40 °C to 60 °C;
$\left(\frac{\Delta n_{\mathrm{abs}}}{\Delta T} \right)_{60,80}$	is the temperature coefficient of absolute refractive index at 60 °C to 80 °C;
T	is an arbitrary temperature (°C).

Annex C
(informative)

Temperature coefficient of refractive index under continuous temperature change

When the light from the light source enters perpendicularly to the surface of an optical glass specimen polished on a parallel plane, which has a specimen length L and absolute refractive index n_{abs}, interference stripes are generated by interference by the light reflected from the front surface and back. When the temperature of the specimen is changed continuously, the change in the length of the specimen (ΔL) and that in the refractive index (Δn_{abs}) cause the change in the optical path length ($2 \times \Delta s$) for the light path reciprocal in the specimen. Read this change in optical path length as the number of cycles [f (hereinafter referred to as cycle number)] of light/dark change in interference stripes. Simultaneously, also read the temperature change (ΔT) of the specimen and calculate the temperature coefficient of the change in optical path length. The temperature coefficient for this change in optical path length is expressed as the sum of the temperature coefficient [$(\Delta n_{abs}/\Delta T) \times L$] for the change in optical path length due to the temperature coefficient of refractive index and the temperature coefficient [$(\Delta L/\Delta T) \times n_{abs}$] for the change in optical path length due to linear expansion [see Formula (C.1)]. The temperature coefficient of the refractive index is derived by subtracting the product of the linear expansion coefficient [$\Delta L/(L \times \Delta T)$] and the refractive index in a given temperature range from the product of the temperature coefficient ($\Delta s/\Delta T$) and ($1/L$) of the change in optical path length [see Formula (C.2) and Formula (C.3)].

$$\frac{\Delta s}{\Delta T} = \frac{\Delta n_{abs}}{\Delta T} \times L + \frac{\Delta L}{\Delta T} \times n_{abs} \tag{C.1}$$

$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{L} \times \frac{\Delta s}{\Delta T} - \frac{1}{L} \times \frac{\Delta L}{\Delta T} \times n_{abs} \tag{C.2}$$

It is also possible to replace the linear expansion coefficient as α_l and express as Formula (C.3).

$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{L} \times \frac{\Delta s}{\Delta T} - \alpha_l \times n_{abs} \tag{C.3}$$

The change in optical path length by the interferometry is calculated by Formula (C.4) using the interferometer scale factor (1/2), which takes the setup conditions of a double pass interferometer configuration into account, the number of cycles (f) of light/dark change of interference stripes and the wavelength of light source for optical path length change measurement (λ).

$$\Delta s = \frac{1}{2} \times f \times \lambda \tag{C.4}$$

When Formula (C.4) is substituted into Formulae (C.3) to (C.5) can obtain the temperature coefficient of the absolute refractive index.

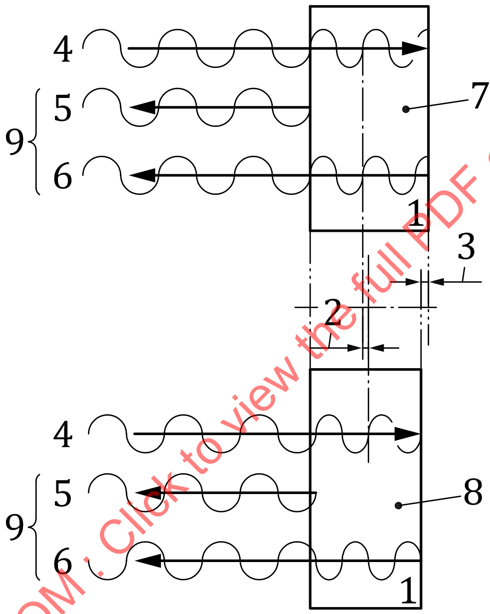
$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{2} \times \frac{f \times \lambda}{L \times \Delta T} - \alpha_l \times n_{abs} \tag{C.5}$$

In Formula (C.5), the refractive index of the specimen in the term ($-\alpha_l \times n_{abs}$) to remove the change in optical path length caused by linear expansion is the absolute refractive index (n_{abs}), but even when the relative refractive index (n_{rel}) is used for calculation, the difference is small, and the difference is limited to approximately 6×10^{-9} K^{-1} at maximum in the temperature coefficient of refractive index of general optical glass. Therefore, in consideration of the convenience of data processing, the temperature coefficient of the absolute refractive index may be calculated using Formula (C.6) using the relative refractive index.

$$\frac{\Delta n_{abs}}{\Delta T} = \frac{1}{2} \times \frac{f \times \lambda}{L \times \Delta T} - \alpha_l \times n_{rel} \quad (C.6)$$

From the temperature coefficient of absolute refractive index obtained in Formula (C.5) or Formula (C.6), calculate the temperature coefficient of relative refractive index in Formula (6) of 8.3. The absolute refractive index at the upper and lower boundary temperature with ΔT temperature width, which is necessary there, is calculated from Formula (B.1) or Formula (B.2) of Annex B, using the relative refractive index $n_{rel}(T_0)$ measured with the reference temperature T_0.

A conceptual diagram of the principle of measurement is shown in Figure C.1. This figure shows that when the temperature of specimen changes, the refractive index of specimen and the specimen length will change, then the optical path length will change, which shifts the phase of the backside reflected light of specimen, causing a change in the intensity of the interfering light between the backside reflected light and the front surface reflected light.



Key

1 specimen

2 wavelength change ($\Delta\lambda$) inside the specimen due to temperature coefficient of refractive index($\Delta n/\Delta T$)

3 length change(ΔL) of the specimen due to the linear expansion coefficient(α_l)

4 incident light

5 reflected light from the front face of the specimen

6 reflected light from the back face of the specimen

7 condition 1

8 condition 2

9 interference

Figure C.1 — Conceptual diagram of light path length change and reflection light interference in the specimen associated with temperature change

NOTE Condition 1 and Condition 2 have different temperatures.

Annex D
(informative)

Sensor specifications

D.1 Selection of sensors

Image sensors with spatial resolution, such as CCD sensors, and photosensors without spatial resolution, such as photodiodes and phototransistors, can be used in this method. If the interference fringes contain tilt element, i.e. if more than one interference fringe is observed within the observation area. A photo sensor without spatial resolution deteriorates the light/dark contrast of the fringes, but this can be solved by using an image sensor with spatial resolution. The instrument shall be sensitive to the measurement wavelength. The sensor shall be able to resolve the light intensity in the range between maximum and minimum interference signal into at least 10 discrete levels.

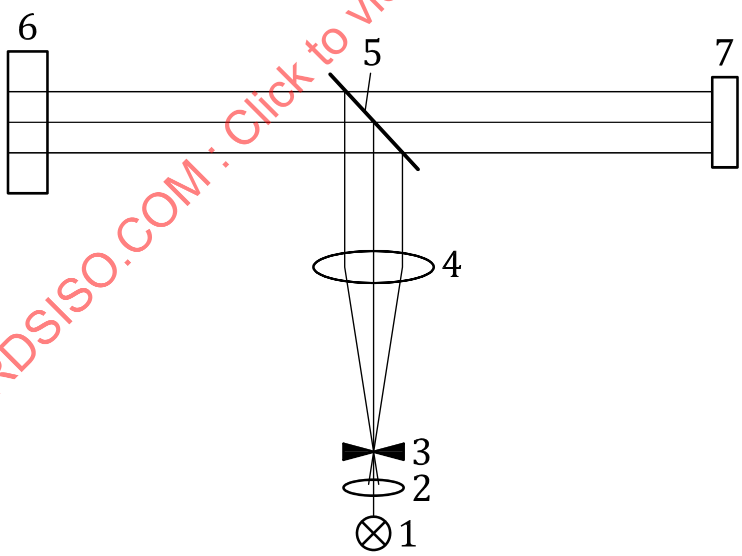
D.2 Image sensor

Image sensor usage is as follows:

a) Fringe image is projected onto the image surface of the image sensor (see Figure D.1).

b) The amount of fringe movement is observed from the information of optical radiation intensity of interference fringes of one or more pixels.

c) Appropriate image processing equipment should be used to extract a usable signal from the sensor.



Key

1 light source
2 condenser lens
3 pinhole
4 collimator lens
5 beam splitter
6 specimen or cavity
7 image sensor

Figure D.1 — Example of setup when using image sensor

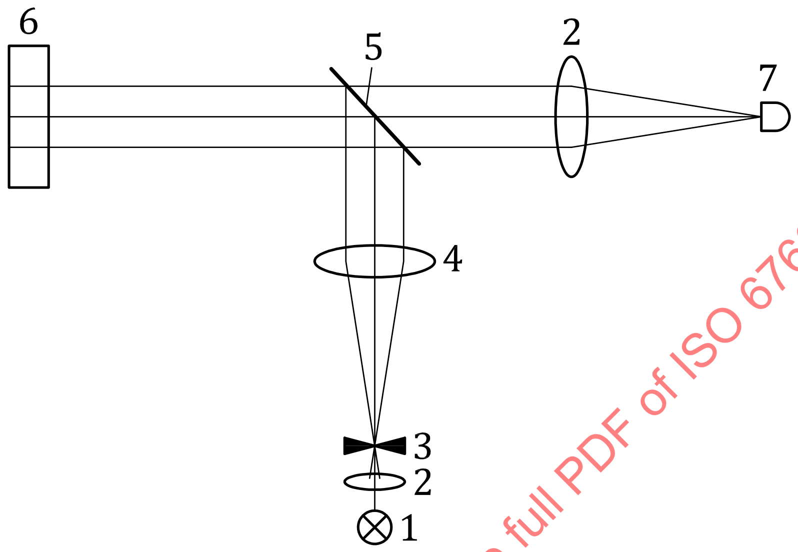
D.3 Photo sensor

Photo sensor usage is as follows.

a) The fringe image is focused on the sensor by a lens or mirror. (see Figure D.2).

b) The amount of fringe movement is observed from information on the intensity of the interfering light incident on the sensor.

c) Appropriate image processing equipment should be used to extract a usable signal from the sensor.



Key

1 light source
2 condenser lens
3 pinhole
4 collimator lens
5 beam splitter
6 specimen or cavity
7 photo sensor

Figure D.2 — Example of setup when using photo sensor

Annex E
(informative)

How to find the deviation of interference fringes between two temperatures

An example of the procedure for determining the amount of the number of cycles of light/dark change of interference shift between two temperatures is shown below.

a) Plot the continuously increasing temperature of the sample versus the output from the detector obtained at that time. (See Figure E.1).

b) Indicate the temperature at the position of the peak and bottom of the brightness of the interference light by numbers, as shown in Figure E.1.

c) In this example, it starts from the peak position, but it can also start from the bottom position. Here is an example of starting from the peak position.

d) The temperature obtained here is the temperature of the 0,5 N period of interference fringe movement.

e) Plot the temperature, T, obtained in b) versus the number of interference fringe shifts, N, (Figure E.2).

f) An arbitrary approximate formula was obtained using the temperature, T, obtained in b) as the explanatory variable and the number of interference fringe moves, N, as the dependent variable. In the example in Figure E.2, a quadratic function shown by Formula (E.1) is used:

$$N = a \times T^4 + b \times T^3 + c \times T^2 + d \times T + e \quad \text{(E.1)}$$

g) The amount of interference fringe shift, P, between temperatures T_i and T_j is obtained as follows.

$$f_{ij} = N_j - N_i \quad \text{(E.2)}$$

where

N is the number of interference fringe moves;

T is the temperature at the peak and bottom position of the fringe intensity (°C);

f_{ij} is the number of cycles of light/dark change of interference fringe shift between temperatures T_i and T_j.