DIGITAL THERMOPILE SENSORS

APPLICATION NOTE

This document is meant to provide an introduction in the functionality and usage of digital thermopile sensors for contactless temperature measurement. Thermopiles are mainly used for contact-less temperature measurement in many applications. Their function is to transfer the heat radiation emitted from the objects into voltage output. Major applications are appliances like microwave oven, clothes dryer, automatic cooking, medical devices like ear and fore head thermometer, automotive applications like car climate control, seat occupancy, blind spot alert, black ice warning, consumer products like printer, copier, mobile phone and many industry applications like paper web, plastic parts etc.

FIGURE 1 Thermopile Component TSD305-1C55

Infrared Temperature Measurement

Any object emits infrared radiation. The radiation power is increasing with growing surface temperatures. Based on this relation, thermopiles measure the emitted power and determine the object's temperature precisely.

Thermopile infrared sensors are based on two physical effects:

- Black body radiation: Any object with a temperature above 0 K emits electromagnetic radiation according Planck's law. The integral over Planck's curve is called the Stefan-Boltzmann-Law which gives the total emitted power:

  $$P = A \cdot \varepsilon \cdot \sigma \cdot T^4$$

  P=emitted power, A=surface area, ε=emissivity of surface,
  σ=Stefan-Boltzmann-Constant=5.67·10-8W/(m2·K4), T=absolute temperature (in K)

- For surface temperatures <700°C this infrared radiation only. If the surface temperature exceeds 700°C an increasing part of the emitted radiation is visible light, e.g. glowing steel, incandescent lamp etc.
- Seebeck effect: Exposing a pair of contacts of dissimilar conductors to a temperature difference results in a voltage difference.

Thermopile Sensor Function

The thermopile infrared sensor consists of an absorber, which is thermally isolated from a frame and in series connected thermocouples. When the absorber is pointed towards an object with a temperature different from the absorber, then the power emitted by object and absorber differs as well. There is a netto radiative heat flow to/from the absorber which is heating/cooling the absorber. This resulting temperature difference between absorber and frame is converted by the thermopile (acc. Definition 1) into a voltage. When also the temperature of the frame is measured, using e.g. a NTC thermistor, the objects temperature can be calculated using the Stefan-Boltzmann-Law.

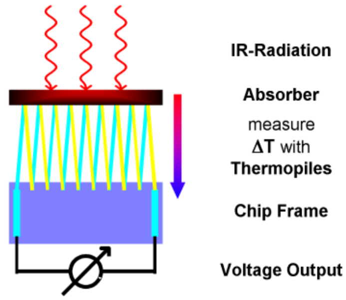


FIGURE 2 Thermopile Chip Composition

Anatomy of Thermopile Sensor Components

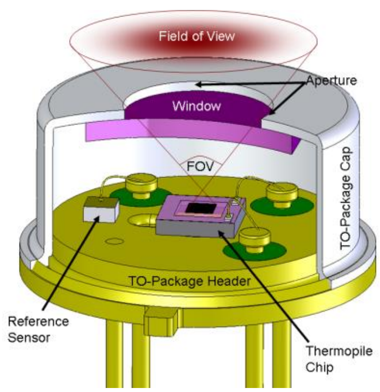


FIGURE 3 Cross section through a Thermopile Sensor

A digital thermopile sensor also contains a signal processing unit.

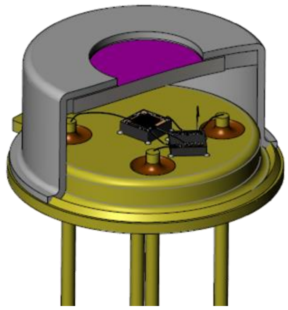


FIGURE 4 Cross section through a Digital Thermopile Sensor

Transport Recommendations

- Avoid touching of silicon window
- Avoid contamination of silicon window
- Avoid damage of silicon window (scratches, etc.)
- Avoid pin deformation
- Avoid compression of component housing

Cleaning Recommendations

- Isopropanol (other names: Iso-Propyl-Acohol (IPA), 2-Propanol), use medical grade, pro analysis grade or purer
- Scratch and lint free cleaning tissue (e.g. Bemcot M-3II)

Using the wet tissue:
Clean from the center of the window or lens to the outside.
Take care that you also clean the tiny step between optics and metal case of the thermopile properly

- Check for stains after wet cleaning, if necessary repeat the wet cleaning
- Check for lints after wet cleaning, if necessary wipe of lints with a dry tissue
- Please Note:
  Some Q-tips have the cotton attached to the stick with glue. In some cases this glue is dissolved by the isopropanol and leaves a deposit on the optics. Due the infrared absorption of this deposit the calibration may be compromised.

Solder Recommendations

Process	Temperature	Max. Duration / s	Comment
Wave Soldering [1]	260°C ±5°C	10	AOI recommended
Hand Soldering [1]	375°C ±10°C	4	Control for flux residue and other contamination on the surface of the PCBA recommended
Reflow Soldering	Not recommended		

[1] Parameter valid only for PB-free soldering process.

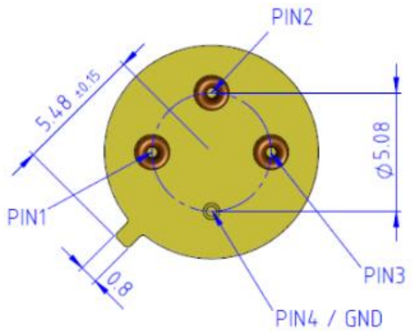
Direct Sunlight

Sun light radiation which is transmitted through a glass window may influence the measurement accuracy. To avoid this, the thermopile sensor is equipped with a long wavelength filter. Due to filter characteristics a small portion of radiation will be added to the radiation of the object. In case of direct sunlight exposure this error can be up to +0.2°C.

Touching the Sensors Cap

User should avoid touching the sensors cap. There will still be a measurement deviation after changing the sensors temperature rapidly.

Setting up Connections



Pin	Name	Type	Function
1	SCL	DI	I²C Clock
2	SDA	DIO	I²C Data
3	V_{DD}	P	Supply Voltage
4	V_{SS}	P	Ground

Status Byte

Each return starts with a status byte followed by the requested data word.

Bit	7	6	5	4	3	2	1	0
Meaning	---	---	Busy	---	---	Memory Error	---	---

- Busy: 1 = Sensor is busy. The requested data is not available yet.
- Memory Error: 1 = Memory integrity check failed. Memory was changed after factory calibration.

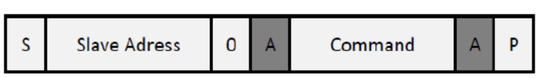
Commands

Note: Each return starts with a status byte followed by the requested data word.

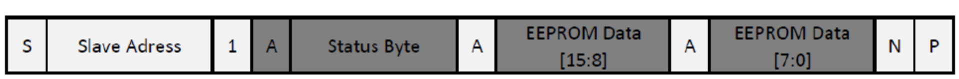
Command	Return	Description
0x00 … 0x39	16 bit EEPROM data	Read data from EEPROM address (0x00 … 0x39) matching the command
0xAF	24 bit object temperature ADC, 24 bit sensor temperature ADC	Measure object temperature and sensor temperature ADC 16 times and calculates mean value. Store data in output buffer.

Read EEPROM

Write Command:



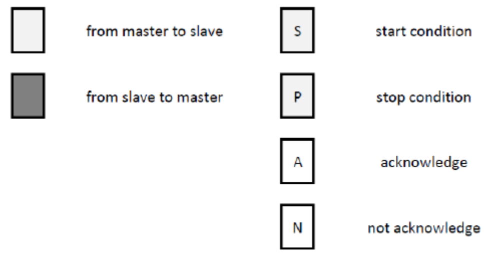
Read EEPROM Data:



Perform Measurement and Read ADC Data

Write Command:

Read ADC Data:



EEPROM Content

Address / hex	Address / dec	Description	Name	Format	Example	
					Content	Value
0x00	0	Lot Nr.	---	UINT16	15001	YY WWW
0x01	1	Serial Number	---	UINT16	12345	Number
0X02	2	I^2C Address Valid range: 0x00 … 0x7F, 0x04 … 0x07 are reserved	I^2CAdd	UINT16	0x00	0
0x03 ... 0x19	2 ... 25	Factory Calibration Data	---	---	---	---
0x1A	26	Min. Sensor Temp. / °C	T_{SenMin}	SINT16	0xFFEC	-20°C
0x1B	27	Max. Sensor Temp. / °C	T_{SenMax}	SINT16	0x0055	+85°C
0x1C	28	Min. Object Temp. / °C	T_{ObjMin}	SINT16	0x0000	0°C
0x1D	29	Max. Object Temp. / °C	T_{ObjMax}	SINT16	0x0064	100°C
0x1E	30	Temperature Coefficient	TC	IEEE 754 H-Word	0xBB96	-0.0046
0x1F	31			IEEE 754 L-Word	0xBB99	
0x20	32	Reference Temperature	T_{REF}	IEEE 754 H-Word	0x41D7	26.93
0x21	33			IEEE 754 L-Word	0x70A4	
0x22	34	Compensation Coefficient k4	$k4_{comp}$	IEEE 754 H-Word	0x3A07	5.161E-04
0x23	35			IEEE 754 L-Word	0x4C8C	
0x24	36	Compensation Coefficient k3	$k3_{comp}$	IEEE 754 H-Word	0x3F10	5.639E-01
0x25	37			IEEE 754 L-Word	0x5CEC	
0x26	38	Compensation Coefficient k2	$k2_{comp}$	IEEE 754 H-Word	0x4367	2.311E+02
0x27	39			IEEE 754 L-Word	0x0D1F	
0x28	40	Compensation Coefficient k1	$k1_{comp}$	IEEE 754 H-Word	0x4724	4.207E+04
0x29	41			IEEE 754 L-Word	0x5A6F	
0x2A	42	Compensation Coefficient k0	$k0_{comp}$	IEEE 754 H-Word	0xC9A0	-1.312E+06
0x2B	43			IEEE 754 L-Word	0x254D	
0x2C	44	Not used	---	---	---	---
0x2D	45			---	---	
0x2E	46	ADC → T Coefficient k4	$k4_{Obj}$	IEEE 754 H-Word	0x944B	-1.029E-26
0x2F	47			IEEE 754 L-Word	0xD24F	
0x30	48	ADC → T Coefficient k3	$k3_{Obj}$	IEEE 754 H-Word	0x2052	1.787E-19
0x31	49			IEEE 754 L-Word	0xF1C2	
0x32	50	ADC → T Coefficient k2	$k2_{Obj}$	IEEE 754 H-Word	0xABE5	-1.631E-12
0x33	51			IEEE 754 L-Word	0x991B	
0x34	52	ADC → T Coefficient k1	$k1_{Obj}$	IEEE 754 H-Word	0x3797	1.802E-05
0x35	53			IEEE 754 L-Word	0x2BBF	
0x36	54	ADC → T Coefficient k0	$k0_{Obj}$	IEEE 754 H-Word	0x41D7	2.693E+01
0x37	55			IEEE 754 L-Word	0x6DBA	
0x38	56	Status	---	UINT16	TBD	---

Number Format

UINT16

- Description: Unsigned integer
- Bits 16
- Min (dec/hec/bin) 0 / 0x0000 / 0b0000 0000 0000 0000
- Max (dec/hec/bin) 65,535 / 0xFFFF / 0b1111 1111 1111 1111

SINT16

- Description: Signed integer
- Bits 16
- Min (dec/hec/bin) - 32,768 / 0x8000 / 0b1000 0000 0000 0000
- Max (dec/hec/bin) 32,767 / 0x7FFF / 0b0111 1111 1111 1111

FLOAT IEEE 754

- Description: Float
- Bits 32
- Min (dec/hec/bin) -1.4E-45 / 0x80000001 / 0b1000 0000 0000 0000 0000 0000 0000 0001
- Max (dec/hec/bin) 3.403E38 / 0x7f800000 / 0b0111 1111 1000 0000 0000 0000 0000 0000
- Example: H-Word 0x3DCC
  L-Word 0xCCCD
  → 0b0011 1101 1100 1100 1100 1100 1100 1101
  → 0.1

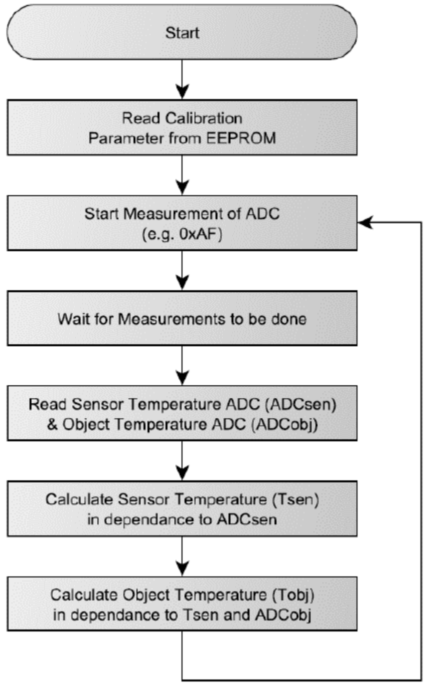
FLOAT IEEE 754 Conversions

The two integer words can easily be converted to a floating-point number by using a union consisting of an integer array and a float.

```
void main(void)
{
   union
   {
         unsigned int iValue[2];    // 16bit unsigned integer
         float fValue;              // float IEEE 754
   } MyUnion;

   while(1)
   {
         MyUnion.iValue[1] = 0x3dcc;
         MyUnion.iValue[0] = 0xcccd;
         //MyUnion.fValue = 0.1;
   }
}
```

Temperature Calculation



Sensor Temperature

The sensor temperature T_{Sen} is calculated from the corresponding 24 bit ADC value ADC_{sen}.

Name	Description	Format	Range	
			Min	Max
ADC_{sen}	ADC Sensor Temperature	INT24	0	16,777,216

ADC_{sen} is scaled to cover the complete sensor temperature range from T_{SenMin} to T_{SenMax}.

Adress / hex	Adress / dec	Description	Name	Format	Example	
					Value	Max
0x1A	26	Min. Sensor Temp. / °C	T_{SenMin}	SINT16	0xFFEC	-20°C
0x1B	27	Max. Sensor Temp. / °C	T_{SenMax}	SINT16	0x0055	+85°C

Formula:

$$T_{sen} = ADC_{sen} / 2^{24} \times (T_{SenMax} - T_{SenMin}) + T_{SenMin}$$

Example:

$ADC_{sen} = 6,364,157$

T_{sen} = 6,364,157 / 224 × [+85°C – (-20°C)] + (-20°C) = 19.83°C

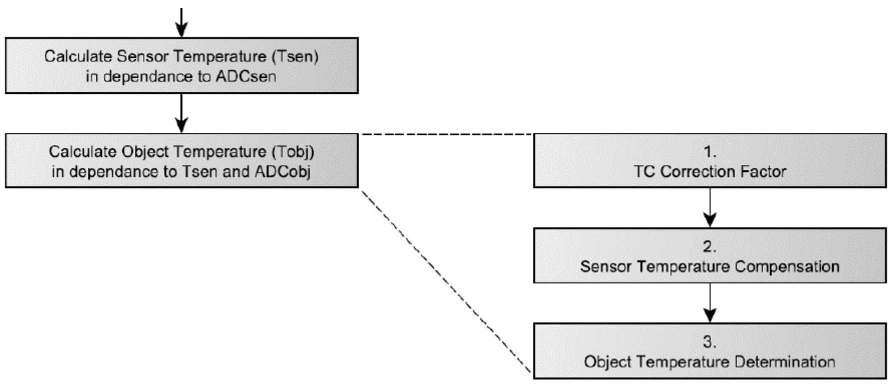
Object Temperature

The object temperature T_{obj} is calculated in dependence of the sensor temperature T_{sen} and ADC_{Obj}.

ADC_{obj} is shifted by 2^{23} in order to provide unsigned integer values for positive and negative measurement values.

Name	Description	Format	Range	
			Min	Max
ADC_{obj}	ADC Object Temperature Shifted by 2^{23} (0 is represented by 8,388,608)	INT24	0	16,777,216

The process consists of three successive steps.



TC Correction Factor

Adress / hex	Adress / dec	Description	Name	Format	Example	
					Content	Value
0x1E	30	Temperature Coefficient	TC	IEEE 754 H-Word	0xBB96	-0.0046
0x1F	31			IEEE 754 L-Word	0xBB99	
0x20	32	Reference Temperature	T_{REF}	IEEE 754 H-Word	0x41D7	+26.93
0x21	33			IEEE 754 L-Word	0x70A4	

Formula:

$$TCF = 1 + [(T_{sen} - T_{ref}) \times TC]$$

Example:

T_{sen} = +19.83°C

T_{ref} = +26.93°C

TC = -0.0046

$$TCF = 1 + [(19.83 - 26.93) \times -0.0046]$$

$$= \underline{1.0327}$$

Temperature Compensation

Adress / hex	Adress / dec	Description	Name	Format	Example	
					Content	Value
0x22	34	Compensation Coefficient k4	$k4_{comp}$	IEEE 754 H-Word	0x3A07	5.161E-04
0x23	35			IEEE 754 L-Word	0x4C8C	
0x24	36	Compensation Coefficient k3	$k3_{comp}$	IEEE 754 H-Word	0x3F10	5.639E-01
0x25	37			IEEE 754 L-Word	0x5CEC	
0x26	38	Compensation Coefficient k2	$k2_{comp}$	IEEE 754 H-Word	0x4367	2.311E+02
0x27	39			IEEE 754 L-Word	0x0D1F	
0x28	40	Compensation Coefficient k1	$k1_{comp}$	IEEE 754 H-Word	0x4724	4.207E+04
0x29	41			IEEE 754 L-Word	0x5A6F	
0x2A		Compensation Coefficient k0	$k0_{comp}$	IEEE 754 H-Word	0xC9A0	-1.312E+06
0x2B				IEEE 754 L-Word	0x254D	

Formula:

Offset = $k4_{comp} \times Tsen^4 + k3_{comp} \times Tsen^3 + k2_{comp} \times Tsen^2 + k1_{comp} \times Tsen + k0_{comp}$

$Offset_{TC}$ = Offset × TCF

Example:

T_{sen} = +19.83°C

$k4_{comp}$ … $k0_{comp}$ See table above

Offset = $= 5.161 \cdot 10^{-4} \times 19.83^4 + 5.639 \cdot 10^{-1} \times 19.83^3 + 2.311 \cdot 10^2 \times 19.83^2 + 4.207 \cdot 10^4 \times 19.83 + -1.312 \cdot 10^6$

= -382,399

$Offset_{TC}$ = = -382,399 × 1.0327

= -394,904

Object Temperature Determination

Adress / hex	Adress / dec	Description	Name	Format	Example	
					Content	Value
0x2E	46	ADC → T Coefficient k4	$k4_{Obj}$	IEEE 754 H-Word	0x944B	-1.029E-26
0x2F	47			IEEE 754 L-Word	0xD24F	
0x30	48	ADC → T Coefficient k3	$k3_{Obj}$	IEEE 754 H-Word	0x2052	1.787E-19
0x31	49			IEEE 754 L-Word	0xF1C2	
0x32	50	ADC → T Coefficient k2	$k2_{Obj}$	IEEE 754 H-Word	0xABE5	-1.631E-12
0x33	51			IEEE 754 L-Word	0x991B	
0x34	52	ADC → T Coefficient k1	$k1_{Obj}$	IEEE 754 H-Word	0x3797	1.802E-05
0x35	53			IEEE 754 L-Word	0x2BBF	
0x36	54	ADC → T Coefficient k0	$k0_{Obj}$	IEEE 754 H-Word	0x41D7	2.693E+01
0x37	55			IEEE 754 L-Word	0x6DBA	

Formula:

ADC_{Comp} = $Offset_{TC} + ADC_{Obj} - 2^{23}$

ADC_{CompTC} = ADC_{Comp} / TCF

$$T_{Obj} = k4_{Obj} \times ADC_{CompTC}^4 + k3_{Obj} \times ADC_{CompTC}^3 + k2_{Obj} \times ADC_{CompTC}^2 + k1_{Obj} \times ADC_{CompTC} + k0_{Obj}$$

Example:

ADC_{Obj} = 10,738,758

$k4_{Obj}$ ... $k0_{Obj}$ See table above

ADC_{Comp} = = -394,904 + 10,738,758 – 8,388,608
= 1,955,246

ADC_{CompTC} = = 1,955,246 / 1.0327
= 1,893,334

$$T_{Obj} = -1.029 \cdot 10^{-26} \times 1{,}893{,}334^4 + 1.787 \cdot 10^{-19} \times 1{,}893{,}334^3 + -1.631 \cdot 10^{-12} \times 1{,}893{,}334^2 + 1.802 \cdot 10^{-5} \times 1{,}893{,}334 + 2.693 \cdot 10$$

= 56.28°C

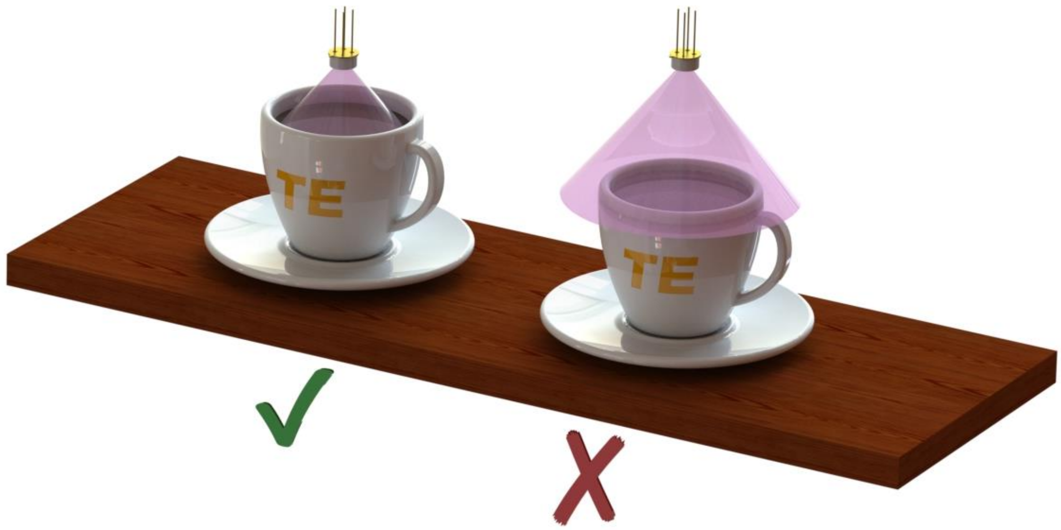
Example Code

This example code is meant to illustrate the basic procedure to determinate the measured sensor and object temperatures with respect to TSD digital thermopile sensors. This code needs to be modified with respect to the compiler used.

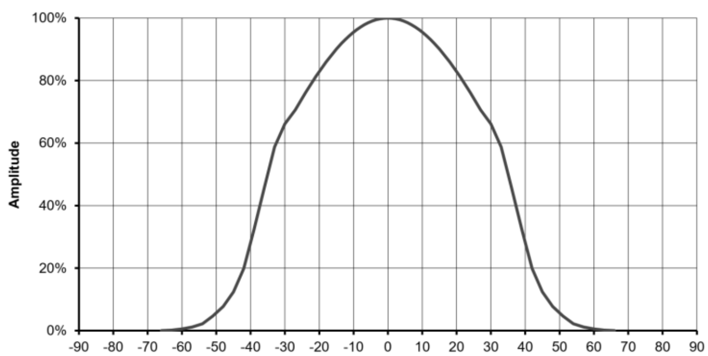
```
//*****************************************************************************************//
// File: TSD_Temperature_Determination_Example.c //
// Date: 01.11.2016 //
// Description: This example code is meant to illustrate the basical procedure //
// to determinat the measured sensor and object temperatures with //
// respect to TSD digital thermopile sensors. //
// This code is not meant to work or to be compiled. //
//*****************************************************************************************//
void TSD_Determinate_Temperature(void)
{
        signed int siMinObjTemp, siMaxObjTemp, siMinSenTemp, siMaxSenTemp;
        float fTC, fTref, fK4com, fK3com, fK2com, fK1com, fK0com, fK4obj, fK3obj,
        fK2obj, fK1obj, fK0obj;
        float fTsen, fTobj;
        float fTCF, fOffset, fADCcomp;
        signed long slADC_Object, slADC_Sensor;
        // Read Temperature Range Minimum & Maximum
        siMinSenTemp = (signed int)Read_EE_UInt(26);
        siMaxSenTemp = (signed int)Read_EE_UInt(27);
        siMinObjTemp = (signed int)Read_EE_UInt(28);
        siMaxObjTemp = (signed int)Read_EE_UInt(29);
        // Read all necessary coefficients from the memory, float tye
        fTref = Read_EE_Float(32);
        fTC = Read_EE_Float(30);
        fTref = Read_EE_Float(32);
        fK4com = Read_EE_Float(34);
        fK3com = Read_EE_Float(36);
        fK2com = Read_EE_Float(38);
        fK1com = Read_EE_Float(40);
        fK0com = Read_EE_Float(42);
        fK4obj = Read_EE_Float(46);
        fK3obj = Read_EE_Float(48);
        fK2obj = Read_EE_Float(50);
        fK1obj = Read_EE_Float(52);
        fK0obj = Read_EE_Float(54);
        // Read ADC Values for Object Temp. & Sensor Temp.
        Read_ADC_Values(&slADC_Object, &slADC_Sensor);
        // Calculate Sensor Temp. (slADC_Sensor, Minimum & Maximum Sensor Temp.), Page 8
        fTsen = (float)slADC_Sensor / 16777216.0 * (siMaxSenTemp - siMinSenTemp) + siMinSenTemp;
        // Calculate TC Correction Factor (Temp. Coefficient & Reference Temp.), Page 9fTCF = 1.0
        + ((fTsen - fTref) * fTC);
        // Calculate Offset Value, Page 10
        fOffset = fOffset + fK4com * fTsen * fTsen * fTsen * fTsen;
        fOffset = fOffset + fK3com * fTsen * fTsen * fTsen;
        fOffset = fOffset + fK2com * fTsen * fTsen;
        fOffset = fOffset + fK1com * fTsen;
        fOffset = fOffset + fK0com;
        fOffset = fOffset * fTCF;
        // Align ADC Value for Object Temperature, Page 11
        slADC_Object = slADC_Object - 8388608;
        // Calculate Object Temperature, Page 11
        fADCcomp = (float)slADC_Object + fOffset;
        fADCcomp = fADCcomp / fTCF;
        fTobj = fTobj + fK4obj * fADCcomp * fADCcomp * fADCcomp * fADCcomp;
        fTobj = fTobj + fK3obj * fADCcomp * fADCcomp * fADCcomp;
        fTobj = fTobj + fK2obj * fADCcomp * fADCcomp;
        fTobj = fTobj + fK1obj * fADCcomp;
        fTobj = fTobj + fK0obj;
        // Resulting Sensor Temperature = fTsen
        // Resulting Object Temperature = fTobj
 }
```

Field of View

The thermopile's field of view must be directed to the object surface of interest. The distance to the surface or the surface diameter must be adjusted to ensure that the complete sensors field of view is covered by the object, see example on the left in the picture below.

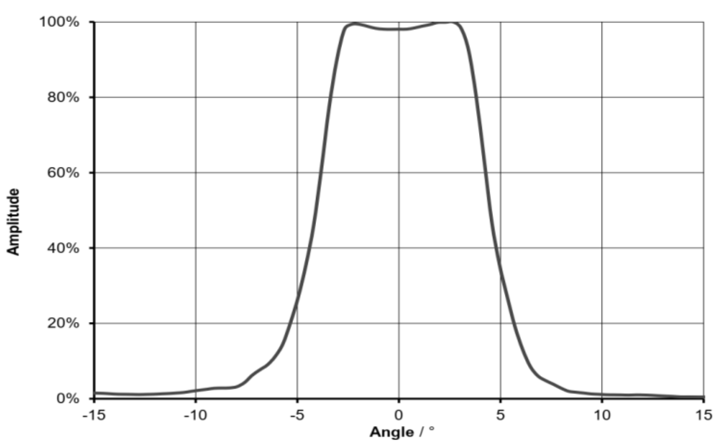


TSD305-1C55
TSD305-2C55



Distance / mm	Min. Diameter / mm
10	24
20	43
30	62
40	82
50	101
100	198
200	391
300	584
400	777
500	970

TSD305-1SL10



Distance / mm	Min. Diameter / mm
10	6
20	8
30	10
40	11
50	13
100	22
200	39
300	57
400	74
500	92

Emissivity

Every object is transmitting infrared energy in dependence to its temperature. The emissivity is the ratio of the radiated power by an object to the radiation of an ideal black body. Common materials like liquids, clothes, human skin, foods have emissivity factors >0.90 and therefore they can be measured very accurately without adopting the sensors specification.

To compensate the measurement for an object with significant low emissivity, ADC_{obj} needs to be adjusted.

Name	Description	Format	Range	
			Min	Max
ADC_{obj}	ADC Object Temperature Shifted by 2^{23} (0 is represented by 8,388,608)	INT24	0	16,777,216

Formula:

ADC_{Corr} = $(ADC_{Obj} - 2^{23}) / 0.9$

Example:

ADC_{Obj} = 10,738,758

$Emissivity_j$ 0.9 (90%)

ADC_{Corr} = = 2,611,278

Material	Emissivity
Aluminum	
Polished	0.10 – 0.05
Oxidized	0.10 – 0.40
Rough	0.10 – 0.30
Anodized	0.60 – 0.95
Asphalt	0.90 – 1.00
Brass	
Polished	0.05
Oxidized	0.50 - 0.60
Burnished	0.30
Ceramic	0.90 – 0.95
Copper	
Polished	0.10
Oxidized	0.20 – 0.80
Foods	0.85 – 1.00
Gold	0.05
Glass	
Plate	0.90 – 0.95
Fused quartz	0.75

Material	Emissivity
Human Skin	0.99
Iron	
Polished	0.20
Oxidized	0.50 - 0.95
Rusted	0.50 – 0.70
Paint	
Aluminum paint	0.50
Bronze paint	0.80
On metal	0.60 – 0.90
On plastic, wood	0.80 – 0.95
Paper	0.85 – 1.00
Plastic	0.95 – 1.00
Stainless Steel	
Polished	0.10 – 0.15
Oxidized	0.45 - 0.95
Water	
Liquid	0.90 – 0.95
Ice	0.95 – 1.00
Snow	0.80 – 1.00

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TE CONNECTIVITY

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