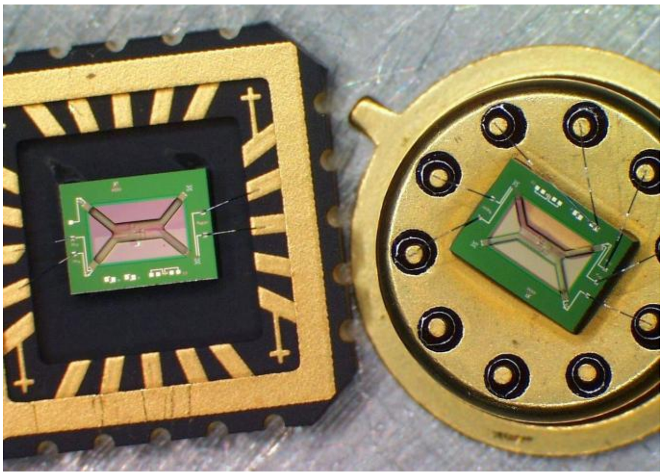
Thermal Conductivity Gauge XEN-TCG3880

for gas type measurement and vacuum measurement



XEN-TCG3880 mounted in LCC-20 (left) and TO-5 (right)

Sander van Herwaarden

1 Introduction

1.1 Short description

The **XEN-TCG3880** is a thermal conductivity gauge (TCG) made using silicon technology. The sensor chip consists of a silicon rim of 2.50 × 3.33 mm, 0.3 mm thick, in which a silicon-nitride membrane is created. In the center is a heater, with a sensor element measuring its temperature.
The chip measures the thermal conductance between the ambient and the center of the membrane, and this depends on several parameters, such as pressure, gas type, and material depositions on the membrane. This dependence upon physical parameters allows the TCG to measure such quantities as absolute pressure, gas mixture composition, and material properties.
The standard housing for the XEN-TCG3880 is a TO-5 10-pins header, other housings are available on request.

The **XEN-TCG3880Pt** has a class B Pt100 platinum temperature sensor on the TO-5 housing, next to the chip. For dat see Table 2.1 on page 3, for a photograph see Connection diagram on page 4.

1.2 Applications

Gas type measurement:

- Measurement of thermal conductivity
- Measurement of concentration of Helium, CO_2, etc, in air
- Measurement of binary gas-mixture composition

Vacuum measurement:

- Vacuum measurement between 10 mPa and 10 kPa
- Sealed gas-enclosure leakage

Calorimetry:

- Ultra-fast calorimetric measurements on polymers
- Calorimetric measurements on spin-coated layers

2 Technical data

Table 2.1: ***Specifications*** *(22 °C and 1 V power supply)*

Parameter	typ*	unit	symbol	notes
Output				
in vacuum at 0 mbar	130	V/W		
in air at 1013 mbar	30	V/W		no upper heat sink
in air at 1013 mbar	6	V/W		with upper heat sink at 20 µm
in helium at 1013 mbar	7	V/W		
Time constant			τ	
in air	9	ms		
in vacuum	*36*	ms		
Stability				
short term	*100*	ppm		1 minute, good temperature stabilisation
long term	*1000*	ppm		1 week, temperature correction
Thermopile				
resistance	55	kΩ	R_{tp}	
effective sensitivity	1.3	mV/K	S_{tp}	Referred to temperature of heater
intrinsic sensitivity	*2.4*	mV/K		Average Seebeck coefficient 0.2 mV/K, 12 leads
temperature coefficient	0.05	%/K		
Heater				
resistance	0.6	kΩ	R_{heat}	
temperature coefficient	0.1	%/K		
Thermal resistance				
membrane	100	kK/W		vacuum output divided by thermopile sensitivity
temperature coefficient		%/K		in vacuum
membrane + gas	23	kK/W		air
temperature coefficient	-0.08	%/K		air
Maximum heating voltage			U_{heat}	
in air	2.5	V		
in vacuum	1	V		
Sensor ambient temperature				Without guarantee for lifetime
minimum	-196	°C		no significant change in output
	-250	°C		probably no significant change in output
	-250 to -273	°C		reduced output
maximum	*240*	°C		tested on similar devices, short times
Heater maximum temperature	250	°C		Long term no drift, absolute maximum rating
XEN-TCG3880Pt				
Pt100 class B	± 0.3	°C		Error at 0 °C

*Values in italics: estimates, not measured

Thermal Conductivity Gauge   XEN-TCG3880

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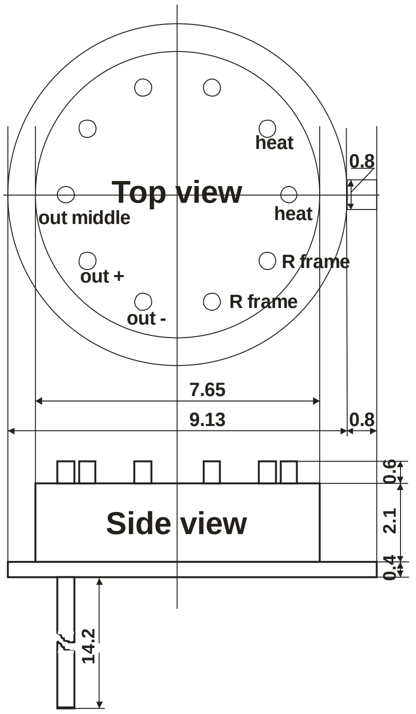
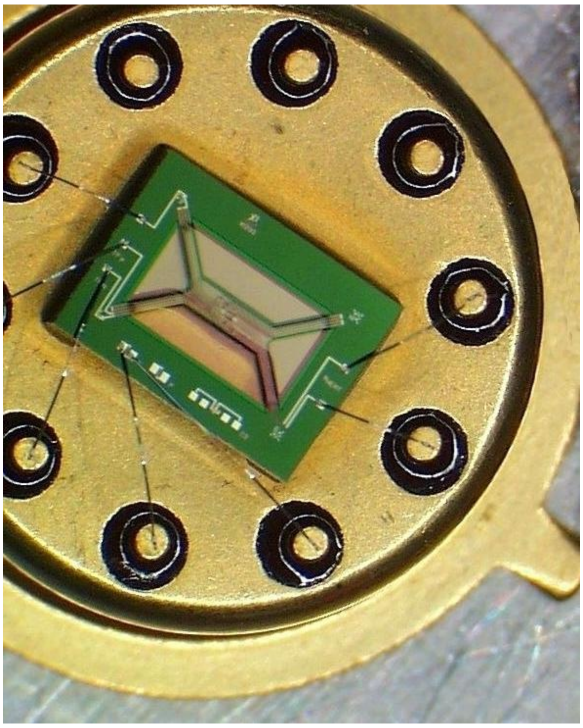
Packaging information (TO5 and LCC-20)

KF-16	KF-16 vacuum flange with TO-5 insert
KF-40	KF-40 vacuum flange with TO-5 or LCC-20 insert
LCC-20	Leadless Chip Carrier (20 pins, 9.5x9.5 mm), available on request
TO-5	Metal TO-5 housing (10 pins round, 9 mm diameter)

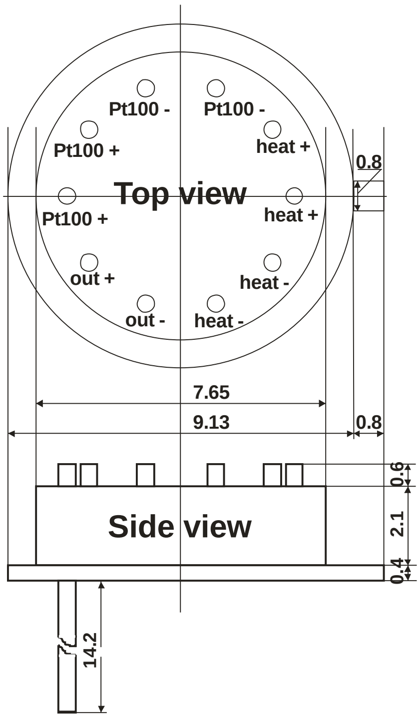
TO-5

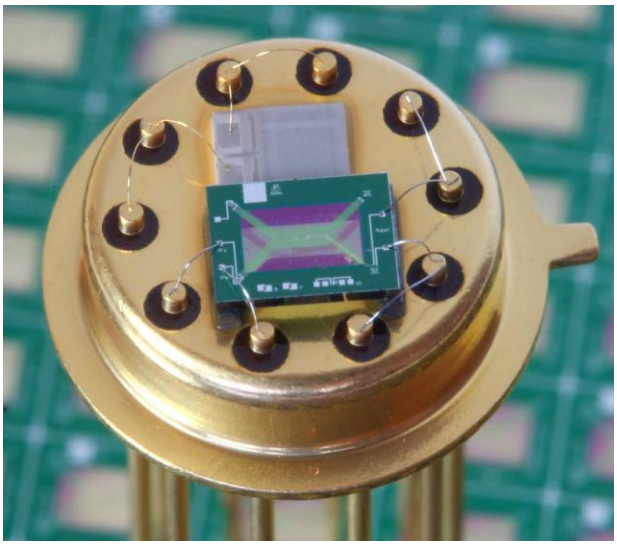




XEN-TCG3880

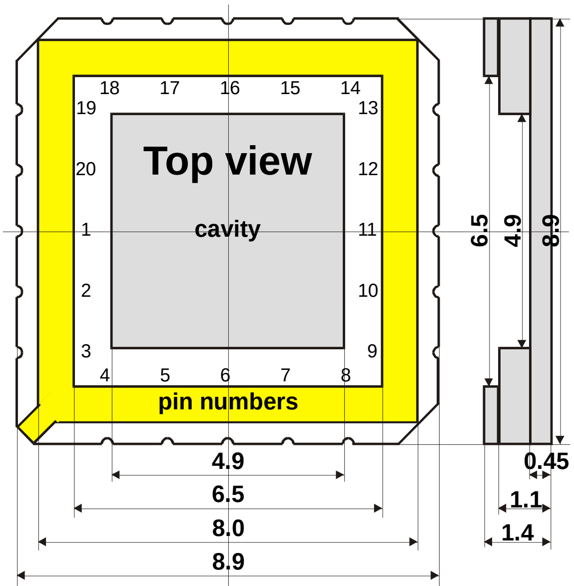
TO-5

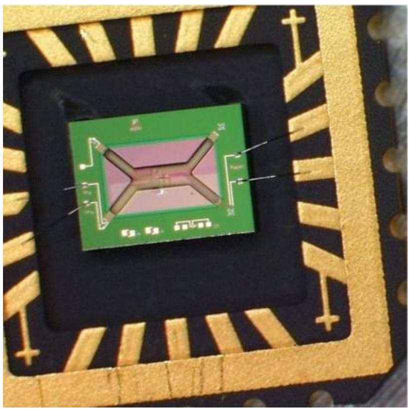


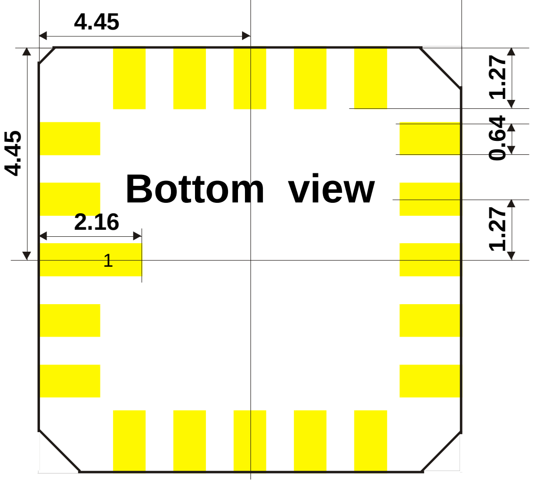


XEN-TCG3880Pt

LCC-20

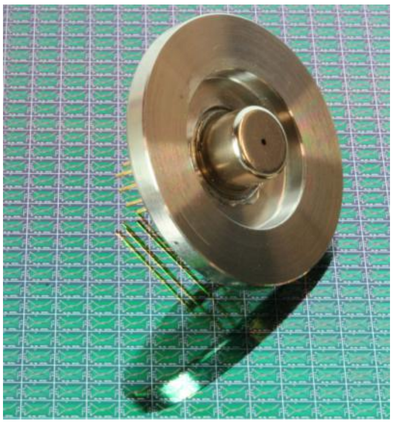






Pin 1 Out + Pin 11 heat
Pin 2 Out - Pin 12 heat

XEN-TCG3880 in KF-16 flange



3 Extended description and general notes on use

3.1 Sensor description

The thermal conductivity gauge XEN-TCG3880 is a thin-film-thermopile thermal conductivity sensor closely related to the traditional thermocouple gauge and the Pirani gauge. It has been designed with a silicon-nitride closed-membrane structure to give high sensitivity and resolution.
The measurement principle relies on the decrease in effective thermal resistance between the sensitive area of the sensor and the ambient, caused by the thermal conductance of the surrounding gas. As such, it can measure:

- type of gas molecules (thermal conductivity measurement).
- pressure of the gas molecules (vacuum measurement).
- material properties (calorimetric measurement).

The stability and accuracy of the thin-film-thermopile vacuum sensors compare favorably with standard Pirani gauges.
The sensor is standard mounted in a TO-5 header, but different housings (such as LCC-20 and encapsulation in KF-16 and KF-40 vacuum flanges) are also available.

3.2 Sensor operation principle

The thermal conductivity gauge performs a measurement of the thermal resistance between the hot junctions of its thermopile in the center of the membrane, and the cold junctions on the thick rim of the chip. This is achieved by heating the center of the membrane using the heater resistor R_{heat}. The resulting temperature increase of the center is measured by the thermopile. The actual temperature increase depends upon the effective thermal resistance between membrane center and ambient, this is influenced by factors such as thermal resistance of the membrane, that of the ambient gas, any present gas flows, and (usually negligible) emitted radiation. Care must be taken to avoid significant incident radiation.

The basic theory of the XEN-TCG3880 measurement operation is given by the following formulae:

$$U_{out} = P_{in} \times S_{tp} / (G_{mem} + G_{gas})$$

where U_{out} is the output voltage of the sensor's thermopile in Volt, P_{in} is the input heating power in Watt, which is given by

$$P_{in} = U_{heat} \times I_{heat} = U_{heat}^2 / R_{heat} = I_{heat}^2 \times R_{heat}$$

with U_{heat} as the heating voltage over and I_{heat} as the heating current through the heating resistance R_{heat}. Note, that the value of R_{heat} is temperature dependent, so that the power dissipated in R_{heat} is also temperature dependent, if the heating is performed from a pure voltage or current source. To eliminate in first order this temperature dependence of P_{in}, you can heat from a voltage (or current) source with an internal series resistance equal to R_{heat}. Another approach is to have a temperature-independent series resistance R_{series}, and measure the voltage U_{series} across that resistance. The input power is then given by:

$$P_{in} = U_{heat} \times I_{heat} = U_{heat} \text{ x } U_{series} / R_{series}$$

The thermopile sensitivity S_{tp} is determined by the technology and thermoelectric characteristics of the sensor, in the case of XEN-TCG3880 it consists of 12 thermostrips, 6 n-type and 6 p-type polysilicon strips which each give a sensitivity of about 0.2 mV/K. In total, the intrinsic thermopile sensitivity is about 2.4 mV/K. However, the thermopile does not exactly measure the tem-

perature of the heater, and the effective sensitivity of the thermopile, when measuring the heater temperature increase versus the silicon frame is only 1.3 mV/K. These values are dependent upon temperature.
Finally, the output signal (or transfer which is the output voltage divided by the input power) also depends on the thermal conductance to the ambient. This conductance is built-up by three components.

The first component is the thermal conductance through the membrane G_{mem}, which is somewhat temperature dependent but otherwise fixed.

The component important for the sensing action is the thermal conductance through the ambient gas G_{gas}. It is the exact value of this last conductance which we want to determine. Around atmospheric pressure (1013 mbar) it is independent of the pressure, and solely a function of gas composition. At pressures below 1 bar, it becomes dependent upon the absolute pressure, and there the sensor can be used for pressure measurement.
Note, that flow can increase the heat taken away from the membrane, just as in a regular flow sensor. As such, the XEN-TCG3880 can also be used for flow sensing. If you want to measure only gas composition, any flows over the membrane are best avoided, therefore.

A third component is the thermal conductance through infrared radiation G_{rad}, but this can usually be neglected. It has not been included in the formula.

The thermal conductance G_{gas} is described below, in which we assume that a heat sink is present above and below the membrane of the sensor.
For very low pressures the thermal conductance G between two parallel plates (in W/m^{2}K) is given by:

$$G = G_o P$$

where G_o is the thermal conductivity in W/m^{2}KPa, and P the pressure in pa.

For atmospheric pressures G is given by:

$$G = K / d$$

where K is the thermal conductivity (in W/Km) and d is the distance between the plates. For the whole pressure range the formula becomes:

$$G = G_o \{(PP_t)/(P+P_t)\}$$

Where P_t is the transition pressure, where the thermal conductance in the molecular regime equals that in the viscous regime. P_t depends, upon other things, upon the free mean path λ between collisions of the molecules and the plate distance d. Table 6.1.1 gives the transition pressure and free mean paths for several gases. For vacuum sensors, the value of P_t should be as high as possible, and the plate distance should therefore be as low as possible. This can be achieved by attaching a heat sink very close above the membrane of the XEN-TCG3880, at for instance, 30 μm distance. This will increase the P_t by a factor of 10 compared to the heat sink below the membrane at 300 μm.

Table 3.1: Thermal conductivity and free mean paths for selected gases

Gas type	λ at 1 Pa in mm	P_t at 0.3 mm in Pa	G_o in W/m^{2}KPa	K in mW/Km	G (1 bar, d 0.3 mm) in W/m^{2}K
argon	7.1	90	0.66	18.0	60
helium	19.8	600	0.84	151.0	500
Nitrogen	6.7	90	0.95	25.7	86
Oxygen	7.3	90	1.00	26.2	87
water vapor	4.6	35	1.90	19.9	66

3.3 Temperature coefficient of the XEN-TCG3880

To get an idea of the Temperature Coefficient (TC) of the XEN-TCG3880 we will evaluate the output voltage U_{tp} (in V) of the XEN-TCG3880 thermopile as given by the following formula:

$$U_{out} = U_{\mathrm{tp}} = P \times N\alpha_{\mathrm{s}} \times R_{\mathrm{th}}$$

where P is the input power in W, $N\alpha_{\mathrm{s}}$ is the sensitivity of the thermopile in V/K (N is the number of strips and α_{s} is the average Seebeck coefficient per strip) and R_{th} is the thermal resistance in K/W. All these three factors are temperature dependent.

TC of the power

Power is supplied by biasing the polysilicon heating resistor R_{h} ($\approx 600\ \Omega$). The temperature coefficient of this resistor is about 0.1 %/K (0.6 Ω/K). If we bias with a temperature-independent voltage U_{h}, the power is equal to $U_{\mathrm{h}}^2/R_{\mathrm{h}}$ and the temperature coefficient of the power is –0.1 %/K, the inverse of that of the heating resistor. If we bias with a current I_{h} (or from a voltage source with a large resistance in series), the power is $I_{\mathrm{h}}^2 R_{\mathrm{h}}$ and the TC is now +0.1 %/K, the same as the TC of R_{h}.

This allows us to vary the overall TC by ±0.1 %/K by using either voltage or current biasing. By biasing from a voltage source with a series resistance equal to R_{h} the TC of the power becomes approximately zero.

TC of the thermopile

The thermopile sensitivity $N\alpha_{\mathrm{s}}$ has a technologically determined TC, and for the XEN-TCG3880 it is approximately +0.15 %/K at room temperature. This means that the thermopile output will rise approximately 0.15%/K for a given temperature difference across the thermopile.

TC of the thermal resistance

The most complicated factor is the thermal resistance. The thermal resistance and its TC depend upon the use of the sensor.

In vacuum

At low pressures (1 Pa or less), the thermal resistance is almost completely determined by the membrane. For the XEN-TCG3880, the thermal resistance of the membrane is determined largely by the (low-stress LPCVD) silicon-nitride. That means that the TC in vacuum is determined by that of the SiN (which is estimated to be +0.05 %/K).

Using the XEN-TCG3880 as gas type sensor

When using the TCG to determine gas type or gas mixtures, the situation is different.

For air at atmospheric pressure (100 kPa), the output of the TCG is only 25% of the output at 0 Pa. That means that the thermal conductance G_{th} to the ambient (the inverse of the thermal resistance) is for 75% determined by gas conduction. Thus, the TC of the gas conduction will contribute for 75% to the TC of the thermal resistance. The TC of the thermal *conductivity* of gases is typically of the order of +0.3 %/K at room temperature, which means that the thermal resistance due to gas conductance will decrease with increasing temperature. For air, with a TC of the conductivity of 0.29 %/K, assuming that the membrane resistance will increase at a rate of 0.05 %/K, this will give a TC of R_{th} of $0.25\times0.05\%/\mathrm{K} + 0.75\times{-0.29}\%/\mathrm{K} = -0.2\ \%/\mathrm{K}$.

When the sensor is immersed in pure helium, the situation becomes different again. The output is decreased by another factor of 4, because of the high thermal conductivity of helium. Now, R_{th} is almost entirely determined by the helium, and the TC of R_{th} also. The TC of the conductivity of helium is about 0.24 %/K at room temperature, so that the TC of R_{th} is now slightly larger at –0.24 %/K.

Overall TC of the XEN-TCG3880

Table 3.2 gives an overview of the various TCs for the different measurement situations. It is explained below.

Table 3.2: Temperature coefficients of the XEN-TCG3880 in various situations

Situation	TC thermopile	TC power	TC thermal resistance	Overall TC
Vacuum sensor				
Heating voltage, 0 Pa	+0.15 %/K	-0.10 %/K	+0.05 %/K	**+0.10 %/K**
Heating voltage, 100 kPa	+0.15 %/K	-0.10 %/K	-0.20 %/K	**-0.15 %/K**
Gas type sensor (air)				
Heating voltage	+0.15 %/K	-0.10 %/K	-0.20 %/K	-0.15 %/K
Heating current	+0.15 %/K	+0.10 %/K	-0.20 %/K	+0.05 %/K
Heating voltage + 2 kΩ series resistance	+0.15 %/K	+0.05 %/K	-0.20 %/K	**0.00 %/K**

For vacuum sensor

The overall TC of the XEN-TCG3880 is now the sum of the components, we obtain for a vacuum sensor at 0 Pa a TC of +0.15 %/K (thermopile) +0.05 %/K (thermal resistance of membrane) ±0.10 %/K (power) = +0.10 to +0.30 %/K.

At 0 Pa, a near-zero TC is not possible. Biasing with a pure voltage is to be recommended, since the thermopile and the membrane both give a positive TC. Obtaining a near-zero TC for a vacuum sensor over the whole pressure range from 0-100 kPa is not possible by a simple biasing scheme, as can be deducted from the situation for the gas type sensor. Feed back of the output signal is required allowing the heating to be dependent upon output signal and temperature. Even then, measuring sub-atmospheric pressures of different gas types will lead to problems, as shown for the helium and air examples.

For gas type sensor

For a gas type sensor measuring air we obtain a TC of +0.15 %/K (thermopile) –0.20 %/K (thermal resistance) ±0.10 %/K (power) = -0.15 %/K to +0.05 %/K.

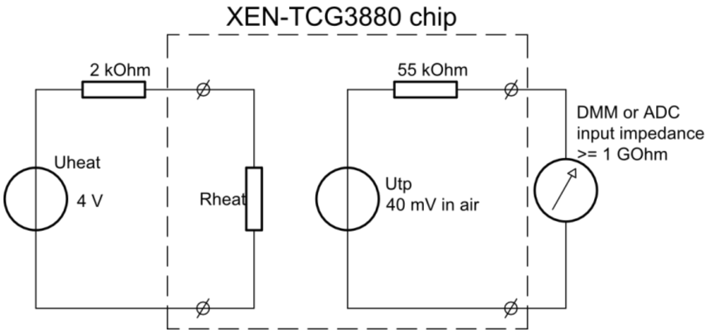
Therefore, by heating from a voltage source with a series resistance of the order of 2 kΩ, a near-zero TC can be obtained.

3.4 Electronics and Biasing of the XEN-TCG3880

Constant voltage biasing

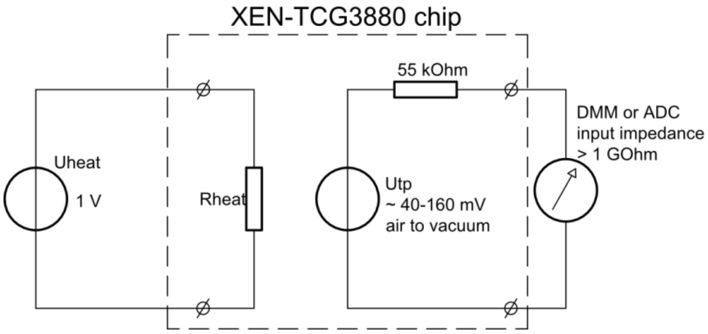
The operation and read-out of the XEN-TCG3880 can be done very simple. A non-feedback type of biasing is the easiest to implement. In this case, the heater is supplied with a constant voltage, current, or power supply of mixed characteristic. The output voltage is measured using a (digital) multimeter (DMM) or using an AD-converter. If the DMM is of adequate quality and with sufficient input resistance, it can directly measure the output voltage of the XEN-TCG3880. The simplest biasing scheme for a gas-type determination is shown in Figure 3.1, where a series resistance of 2 kOhm is inserted before the heater to minimize the overall temperature coefficient of the output voltage (see Sect. 3.3).

Figure 3.1: Constant voltage biasing of the XEN-TCG3880 with 2 kOhm series resistance for minimizing output voltage temperature coefficient in case of gas type measurement.



For vacuum measurements, no simple temperature coefficient elimination is possible over the entire pressure range from 0 Pa to 100 kPa, and the best is to bias from a pure voltage source, as shown in Fig. 3.2

Figure 3.2: Constant voltage biasing of the XEN-TCG3880 for vacuum measurement.



Output signal amplifying or buffering

In case of read out of the output voltage with an ADC with inadequate range or input resistance, the output signal needs to be amplified or buffered first. Depending upon the electronics used various OpAmps can be applied. A good and economic opamp for this is the OP177, which has a low offset voltage (60 µV) and not too much input bias current (few nA), thus resulting in an overall low offset voltage and offset voltage drift. The offset voltage is equal to the OpAmp offset voltage, plus the OpAmp input bias current multiplied by the XEN-TCG3880 output resistance of 55 kOhm.

The OP177 has, however, the disadvantage that it does not have a rail-to-rail input or output voltage. For applications where you want to use a single 0-5 V power supply, other OpAmps with rail-to-rail operation at 0-5 V power supply are preferred. Here you should also consider the offset voltage and the input bias current of the OpAmp. Chopper stabilized OpAmps with very low offset (1 μV) and very low input bias currents (picoAmps) can also be interesting in combination with the XEN-TCG3880. Usually speed and slew rate are of less importance, while noise, particularly for chopper OpAmps, might be of importance. A good loop gain can be important to obtain a good input impedance and thus a good accuracy.

Feedback biasing

Using feedback, the output voltage of the sensor can be stabilized or given a predetermined pattern by electronically adjusting the biasing of the heater. This can especially have advantages when using the XEN-TCG3880 as a nano-calorimeter, where a specific temperature profile in time is often required. Here, more elaborate electronics can be required with a DAC imposing the desired output voltage to be compared with the actual output voltage. Such electronics are beyond the scope of this application note.

4 Application: gas sensing

The main applications of the XEN-TCG3880 are in pressure measurement, gas composition measurement, and calorimetry.

For gas composition measurement, many applications can be found. Measurement of helium-air and helium-oxygen mixtures are particularly attractive, due to the fact that the thermal conductivities of helium (150 mW/Km) and air or oxygen (26 mW/Km) are so very different.

Applications are found, amongst others, in lung function measurement equipment, where the total volume of a human's (or animal's?) lung can be determined by a helium dilution measurement. The patient is connected to a machine with a known volume and known helium concentration (typically between 5-10 % initially). Then the patient is asked to breath in and out into the machine, and the helium will divide between the machine's volume and the patient's lung volume. With the final helium concentration and the initial volume and helium concentration, the patient's lung volume can be determined. If we start out with a 10.00% helium concentration, a machine volume of 5.00 liter, and a patient with a lung volume of also 5.00 liter, the helium concentration will be halved to 5.00%. If the helium concentration is determined with an accuracy down to 0.005% helium concentration (50 ppm), the lung volume of the patient can be determined with a 0.2% accuracy, i.e. 5.00 liter ± 0.01 liter.

Other applications are found in diving, where air-helium mixtures are used for deep dives, the sensor can be used for measurement of the helium concentration of the diving mix. Because lives can depend upon the sensor's reading, good care should be taken, that the concentration indication by the sensor is reliable, for instance, by comparing the measurement with a measurement of pure air and of pure helium.

4.1 Accurate formula for binary gas mixtures

For the thermal conductivity K_{mix} of a binary gas mixture of gases 1 and 2 with thermal conductivities K_1 and K_2 and fractions a and $(1-a)$, a formula exists which takes into account the interaction of the gas molecules of different kinds (see RB Bird, WE Stewart and EN Lightfoot, Transport Phenomena, Wiley, New York (1960) 258-260). It is as follows:

$$K_{mix} = aK_1 / [a + (1-a)F_{12}] + (1-a)K_2 / [(1-a) + aF_{21}]$$

where

$$F_{12} = [8(1+M_1/M_2)]^{-0.5} \times [1+(\mu_1/\mu_2)^{0.5} \times (M_2/M_1)^{0.25}]^{2}$$

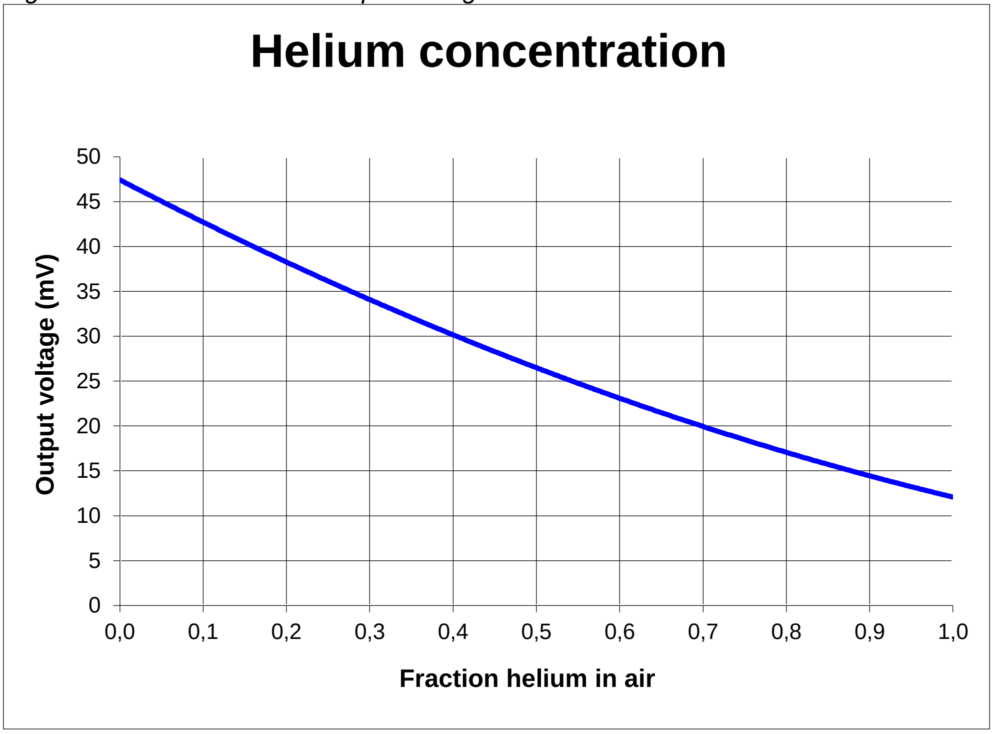
For F_{21}, switch the indices 1 and 2. In this formula, M_1 and M_2 are the molecule weights of both gas types, and μ_1 and μ_2 are their dynamic viscosities (in Pa.s). The formula can conveniently be calculated using mathematical programs, or even using an EXCEL sheet.

At the back of this document data for some selected gases are listed. These data are obtained from the website of NIST (www.nist.gov, see under databases) in the USA, where thermophysical properties of a number of gases are listed.

4.2 Helium sensing

Long term accuracy of helium measurement
For air, the transfer is reduced by a factor of about 4, compared to absence of any gas, i.e., in vacuum. For helium, the output is again reduced by a factor of about 4, compared to the transfer in air. We can assume, in first order, that the sensitivity of the transfer for helium traces in air would be about 2% change in transfer for a change in He concentration from 0 % to 1 %. If we assume a long term stability of the signal of about 0.1%, then we can measure helium concentration accurately down to 500 ppm, assuming temperature stability. Typical temperature dependence of the transfer lies in the order of parts of a %/K, let's assume 0.3 %/K. If we compensate for temperature down to 0.3 K, there is an inaccuracy of about 0.1% due to temperature influences, which is equivalent to the long term stability. Including this factor, the overall accuracy of the sensor for helium measurement would be about 700 ppm on the long term.
Below the output of the XEN-TCG3880 for an air-helium mixture is given at room temperature. The output voltage of the sensor can be approximated by a quadratic formula of helium concentration f_{He}: $U_{out} = U_{out,\,air}\,\{1 - 1.0203 \times f_{He} + 0.2752 \times f_{He}^{2}\}$

Figure 4.1: XEN-TCG3880 output voltage for air-helium mixture.



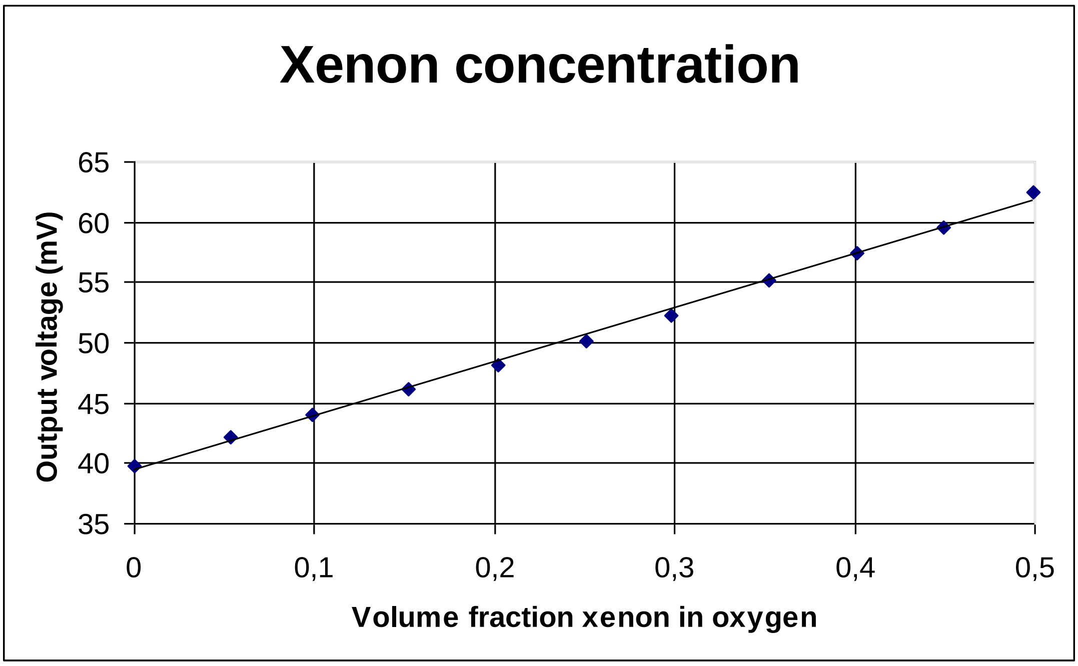
Short term accuracy of helium measurement
For the short term, we may assume a stability ten times better, 100 ppm, and then we could measure helium concentration in air down to about 70 ppm. This would be the limit in concentration measurement that we can obtain without taking extraordinary measures. If we want to obtain an even better performance, we need to measure the output with very good accuracy, supply a very stable input power (and also measure this with adequate accuracy), and our temperature correction or compensation should be adequate. One way of obtaining this is, of course, by chopping the input signal, i.e., by alternatively supplying the gas mixture and a pure air or helium gas to the sensor.
Good temperature stabilization is also helpful. Based on the above, a stabilization of about 1 mK is required to obtain measurement accuracies in the 1 ppm level for helium or hydrogen. For other gases, better measures are necessary since they give lower changes in transfer, because their thermal conductivity is closer to that of air (see the Table at the end of this Note).

4.3 Xenon sensing

Below the output of the XEN-TCG3880 for an oxygen-xenon mixture is given at room temperature. The output voltage of the sensor can be approximated by a linear formula of xenon concentration f_{Xe}: $U_{out} = U_{out,\ oxygen}\{1 + 1.134 \times f_{Xe}\}$

For Xenon in air instead of xenon in oxygen the change in output when adding xenon is about 10% smaller.

Figure 4.2: XEN-TCG3880: Output voltage for Xenon-O_2 mixture



Testing device: XEN-TCG3880 sensor. Test data: by Anzai Medical Co., Ltd., Tokyo, Japan.

4.4 Carbon-dioxide sensing

Carbon-dioxide in air can also be measured thermally, since its thermal conductivity is markedly lower than that of air. For Carbon-monoxide the thermal conductivity is almost the same as for air, so that cannot be measured using a thermal conductivity gauge. The relative sensitivity of the XEN-TCG3880 for low concentrations of CO_2 is measured to be about 0.37, that means, that an increase in CO_2 concentration from 0% to 1% leads to an increase in output signal of 0.37%. With a short-term stability of about 100 ppm, the resolution in CO_2 concentration measurement is then about 250 ppm. By heating the sensor not from a voltage source, but from a voltage source with a series resistance of about 1.5-2 kΩ (having low temperature coefficient), the sensitivity of the output signal for variations in the ambient temperature can be suppressed, increasing the measurement stability.

4.5 Influence of relative humidity RH

The humidity of, for instance, air, will have a slight effect on the output of the sensor. Theoretically, the partial pressure of water vapor at room temperature at 100% RH (relative humidity) is about 3 kPa at 101 kPa pressure. For a change from 0 % RH to 100 % RH, the transfer of the TCG will change about 0.5% in value. Here, a factor of 33 is due to the fact, that 100 % RH is only 3 % partial pressure (at room temperature). Another factor of 4.3 is due to the fact that 1% H_2O mixed into air will result in a decrease of thermal conductivity by only 0.23%, as calculated with the formula for binary gas mixtures. In total there is a mitigation factor of about 145×.

So, the sensor is not very suited to measure RH, but a change in RH may interfere a little bit with the signal. A change of 1 % RH would be (theoretically) equivalent to a change in helium (in a majority of air) concentration of the order of 25 ppm.

This follows from the fact that 1% of helium in air would give about 2% change in transfer. 1 % RH changes the transfer about 50 ppm, and for a 50 ppm change in transfer we would need something like a change in concentration of helium of about 25 ppm.

4.6 Thermal conductivities of gases

Below, some tentative data on a few well-known gases are given to enable prediction of the thermal conductivity of binary mixtures with the formula given above. More data are given in the Tables at the end of this Application Note for some selected gases.

Table 4.1: Approximative thermal conductivities and other data of gases

Gas type		K (0°C) mW/Km	K (25 °C) mW/Km	M kg/kmol	μ (25°C) μPas	μ (0 °C) μPas
Hydrogen	H_2	174	*180*	2.0		8.4
Helium	He	144	151	4.0	19.5	18.6
Neon	Ne	46		20.2		29.7
Methane	CH_4	30	34	16.0	11	10.2
Oxygen	O_2	25	26,2	32.0	20.3	18.9
Air	N_2 (79%) O_2 (21%)	24	26,0	28.8	18.4	17.1
Nitrogen	N_2	24	25,7	28.0	17.8	17
Water vapor	H_2O	16	19,9	18.0	12*	12.5*
Argon	Ar	16	*18*	39.9		21
Laughing gas	N_2O		17,3	44.0	14.9	
Carbondioxide	CO_2	14	16,4	44.0	15.0	13.9
Krypton	Kr	8.7		83.8		23.3
Chlorine	Cl_2	7.6		70.9		16.8*
Xenon	Xe	5.2	*5,4*	131.3		21.0
Radon	Rn		*3,6*	222.0		

* at 100°C

5 Application: vacuum sensor

The XEN-TCG3880 can also be applied as a vacuum sensor, for instance where traditional Pirani gauges and thermocouple gauges are used. With any gaseous ambient, the transfer of the device will start to increase when the ambient pressure falls below 10 kPa. With special measures, such as a heat sink very close to the membrane (a so-called roof), this upper limit of the sensor may be increased up to atmospheric pressure (100 kPa).
Then, the transfer is a function of pressure, until the thermal conduction by the ambient gas becomes so low, that any further changes fall below the noise and instability limit. This constitutes the lower limit of the sensor, and will be around 10 mPa. So, the operational range of the sensor is of the order of 7 decades.
At the lower limit of 10 mPa and the upper limit of 100 kPa, the sensitivity of the sensor is reduced. In the intermediate region, e.g. between 1 Pa and 1 kPa, good measurement accuracy can be obtained, and the pressure can be determined with a typical error of below 1%.
The typical output of the sensor versus pressure is given by the graph in the data sheet, reproduced below.

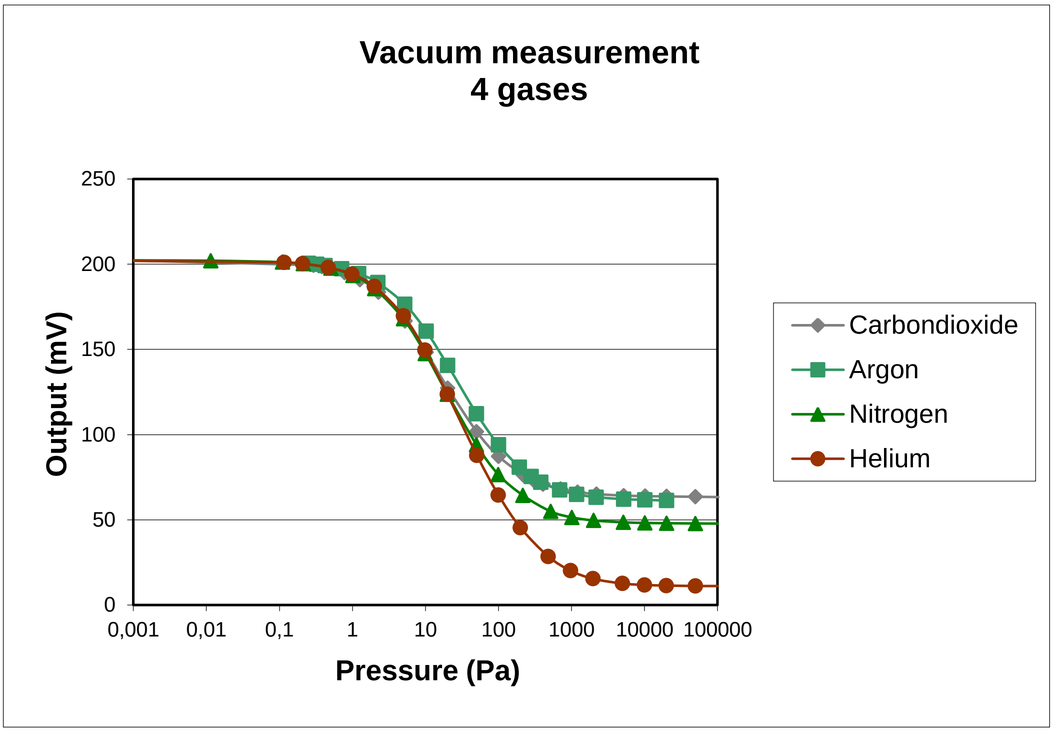
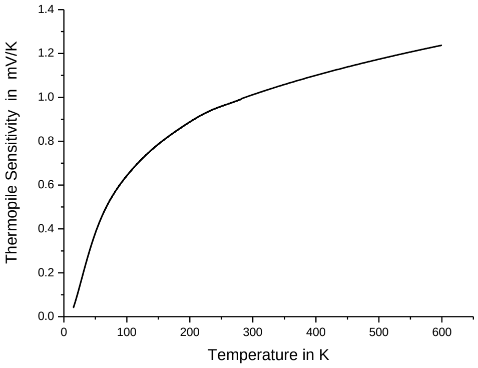


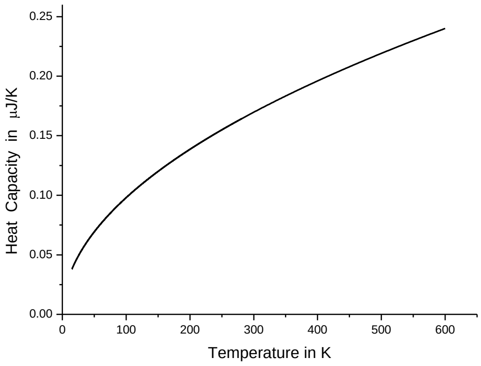
Figure 5.1: XEN-TCG3880 output versus absolute air pressure

6 Application: nano-calorimeter

Application of the XEN-TCG3880 is difficult, since the membrane is very fragile. Depositing a sample onto the membrane requires extreme care, and still then, destruction of the membrane cannot be ruled out. However, the low mass of the membrane enables very fast calorimetry with these devices.
In their article, S.A. Adamovsky et. al. explain their work using the XEN-TCG3880, where cooling and heating rates of up to 5000 K/s were achieved. The measurements have been performed on very small samples, of the order of 1 µg or less. This is an added feature of such small calorimetric chips.



Sensitivity of the thermopile of the XEN-TCG3880, as a function of temperature, assuming 1 mV/K at 300 K
Data from: A.A. Minakov, S.B. Roy, Y.V. Bugoslavsky, L.F. Cohen



Heat capacity of heater + central membrane as a function of temperature

For articles on nanocalorimeters see our website:
www.xensor.nl/txtfiles/hfdfiles/pub.htm

In general for the work of the group of Prof. Schick, see their web site:
www.uni-rostock.de/fakult/manafak/physik/poly/polymerphysics.htm

7 Thermal data for some gases

In this Paragraph some viscosity and thermal conductivity data for selected gases are given versus temperature. The data are taken from the NIST database of thermophysical properties of gases.

This allows to calculate thermal conductivities of mixtures at various temperatures.
The viscosity (in µPa.s) and the thermal conductivity (in mW/Km) can be approximated by a polynomial formula, which can be used for calculating temperature coefficients. Using an Excel spread sheet, the following formulas have been extracted from the data as shown below, with T as the temperature in K. The accuracy of the fit can vary from gas to gas. The tabulated data given on the next pages have the uncertainty as given in the header of data columns. References to the origin of the data is given by NIST in the database (www.nist.gov, item database: thermophysical properties of gases).

Table 7.1: Viscosity + thermal conductivity

gas	viscosity (µPa.s)	thermal conductivity (mW/Km)
Argon	$-30 \times (T/1000)^2 + 85 \times (T/1000) + 0.18$	$-30 \times (T/1000)^2 + 66 \times (T/1000) + 0.15$
Chlorine	$-10 \times (T/1000)^2 + 51 \times (T/1000) - 0.73$	$-20 \times (T/1000)^2 + 56 \times (T/1000) + 4.66$
CO_2	$-20 \times (T/1000)^2 + 59 \times (T/1000) - 1.00$	$-1 \times (T/1000)^2 + 83 \times (T/1000) - 7.74$
CO	$-30 \times (T/1000)^2 + 67 \times (T/1000) + 0.48$	$-30 \times (T/1000)^2 + 94 \times (T/1000) - 0.21$
Helium	$-10 \times (T/1000)^2 + 53 \times (T/1000) + 4.82$	$-100 \times (T/1000)^2 + 418 \times (T/1000) + 37.6$
Hydrogen	$-8 \times (T/1000)^2 + 25 \times (T/1000) + 2.06$	$-90 \times (T/1000)^2 + 553 \times (T/1000) + 27.4$
Nitrogen	$-30 \times (T/1000)^2 + 64 \times (T/1000) + 0.98$	$-30 \times (T/1000)^2 + 90 \times (T/1000) + 1.10$
Oxygen	$-20 \times (T/1000)^2 + 70 \times (T/1000) + 1.78$	$-4 \times (T/1000)^2 + 84 \times (T/1000) + 1.89$

Table 7.2: Viscosity + thermal conductivity of various gases versus temperature

	Argon	Argon	CO2	CO2	CO	CO
Uncertainty	3%	3%	0.5%	5%	5%	5%
T (K)	mW/Km	µPa.s	mW/Km	µPa,s	mW/Km	µPa.s
80					6,8	5,3
85					7,3	5,6
90					7,7	6
95					8,2	6,3
100	6,4	8,2			8,7	6,7
110	7	9			9,7	7,4
120	7,6	9,7			10,6	8
130	8,2	10,5			11,5	8,7
140	8,8	11,3			12,4	9,3
150	9,5	12,1			13,3	9,9
160	10,1	12,9			14,2	10,5
170	10,7	13,7			15	11,1
180	11,3	14,4			15,9	11,7
190	11,9	15,2			16,7	12,2
200	12,4	15,9			17,5	12,8
210	13	16,7			18,3	13,3
220	13,6	17,4	10,84	11,05	19,1	13,8
230	14,1	18,1	11,50	11,56	19,9	14,4
240	14,7	18,8	12,19	12,06	20,7	14,9
250	15,2	19,5	12,90	12,56	21,4	15,4
260	15,7	20,2	13,63	13,05	22,2	15,9
270	16,3	20,8	14,38	13,55	22,9	16,4
280	16,8	21,5	15,16	14,04	23,7	16,8
290	17,3	22,1	15,95	14,53	24,4	17,3
300	17,8	22,8	16,75	15,01	25,1	17,8
310	18,3	23,4	17,56	15,50	25,8	18,2
320	18,8	24	18,38	15,98	26,5	18,7
330	19,3	24,7	19,21	16,45	27,2	19,1
340	19,7	25,3	20,05	16,93	27,9	19,5
350	20,2	25,9	20,89	17,40	28,6	20
360	20,7	26,5	21,73	17,86	29,3	20,4
370	21,1	27	22,57	18,32	29,9	20,8
380	21,6	27,6	23,42	18,78	30,6	21,2
390	22	28,2	24,27	19,24	31,3	21,6
400	22,5	28,8	25,11	19,69	31,9	22
410	22,9	29,3	25,96	20,14	32,6	22,4
420	23,4	29,9	26,80	20,58	33,2	22,8
430	23,8	30,4	27,64	21,02	33,8	23,2
440	24,2	31	28,48	21,46	34,5	23,6
450	24,6	31,5	29,32	21,90	35,1	24
460	25,1	32	30,15	22,33	35,7	24,3
470	25,5	32,6	30,98	22,75	36,3	24,7
480	25,9	33,1	31,81	23,18	37	25,1
490	26,3	33,6	32,64	23,60	37,6	25,4
500	26,7	34,1	33,47	24,01	38,2	25,8
550	28,7	36,6	37,54	26,04	41,2	27,6
600	30,5	39	41,53	28,00	44	29,2
650	32,4	41,3	45,45	29,87	46,9	30,8
700	34,1	43,6	49,28	31,67	49,6	32,4

Table 7.2: Viscosity + thermal conductivity of various gases versus temperature (continued)

	Oxygen	Oxygen	Nitrogen	Nitrogen	Hydrogen	Hydrogen	Chlorine	Chlorine
Uncertainty	2%	0.5%	3%	3%	10%	4%	5%	5%
T (K)	mW/Km	µPa.s	mW/Km	µPa.s	mW/Km	µPa.s	mW/Km	µPa.s
77			7,4	5,4				
80			7,7	5,6				
85			8,2	5,9				
90			8,7	6,3				
95			9,2	6,6				
100			9,7	7				
110			10,6	7,6				
120			11,5	8,3				
130			12,4	8,9				
140			13,3	9,5				
150			14,1	10,1				
160			14,9	10,7				
170			15,8	11,3				
180			16,6	11,8				
190			17,4	12,4				
200	18,37	14,61	18,2	12,9	132,27	6,78		
210	19,22	15,24	19	13,4	138,19	7,01		
220	20,07	15,87	19,7	14	143,91	7,24		
230	20,91	16,48	20,5	14,5	149,55	7,46		
240	21,74	17,09	21,2	15	155,09	7,68	16,8	10,8
250	22,57	17,68	22	15,5	160,44	7,9	17,3	11,2
260	23,39	18,27	22,7	15,9	165,7	8,12	17,8	11,7
270	24,21	18,85	23,5	16,4	170,87	8,33	18,3	12,2
280	25,02	19,42	24,2	16,9	175,85	8,54	18,7	12,6
290	25,83	19,98	24,9	17,3	180,84	8,75	19,2	13,1
300	26,64	20,54	25,6	17,8	185,63	8,95	19,7	13,5
310	27,44	21,09	26,3	18,2	190,43	9,15	20,1	14
320	28,25	21,63	27	18,7	195,04	9,35	20,5	14,4
330	29,05	22,16	27,7	19,1	200,16	9,55	21	14,8
340	29,85	22,69	28,4	19,6	205,18	9,75	21,4	15,3
350	30,65	23,21	29,1	20	210,2	9,94	21,8	15,7
360	31,46	23,73	29,8	20,4	215,14	10,14	22,2	16,1
370	32,26	24,24	30,5	20,8	219,78	10,33	22,6	16,6
380	33,06	24,74	31,1	21,2	224,63	10,52	23	17
390	33,87	25,24	31,8	21,7	229,28	10,7	23,4	17,4
400	34,67	25,74	32,5	22,1	233,94	10,89	23,8	17,8
410	35,48	26,22	33,1	22,5	238,11	11,07	24,2	18,2
420	36,29	26,71	33,8	22,8	242,78	11,26	24,6	18,7
430	37,09	27,18	34,4	23,2	247,46	11,44	24,9	19,1
440	37,90	27,66	35,1	23,6	252,15	11,62	25,3	19,5
450	38,71	28,12	35,7	24	256,84	11,8	25,7	19,9
460	39,51	28,59	36,4	24,4	261,54	11,97	26	20,3
470	40,32	29,05	37	24,8	266,24	12,15	26,4	20,7
480	41,13	29,50	37,6	25,1	270,95	12,32	26,7	21,1
490	41,93	29,95	38,3	25,5	275,67	12,5	27,1	21,5
500	42,74	30,40	38,9	25,9	280,4	12,67	27,4	21,9
550	46,75	32,58	42	27,7	304,11	13,52	29,1	23,9
600	50,73	34,66	45	29,4	327,99	14,34	30,8	25,8
650	54,65	36,67	48	31,1			32,3	27,7
700	58,49	38,62	50,9	32,7			33,8	29,5

Helium Helium Methane Methane

Table 7.2: Viscosity + thermal conductivity of various gases versus temperature (continued)

Uncertainty	0.1%	0.1%	2-10%	2-5%
T (K)	mW/Km	μPa.s	mW/Km	μPa*s
100	74,8	9,6		
120	84,4	10,8		
125			13,08	4,9757
140	93,4	11,9		
150			16,022	5,9357
160	102,1	13,0		
175			18,986	6,8834
180	110,4	14,1		
200	118,5	15,1	21,941	7,8096
225	128,2	16,4	24,905	8,7098
250	137,7	17,6	27,966	9,5824
275	146,9	18,8	31,17	10,427
300	155,9	19,9	34,552	11,245
325	164,6	21,0	38,136	12,037
350	173,2	22,1	41,93	12,805
375	181,6	23,2	45,93	13,549
400	189,9	24,3	50,127	14,272
425			54,505	14,975
450	206,0	26,3	59,048	15,659
475			63,739	16,326
500	221,7	28,3	68,564	16,976
525			73,506	17,610
550			78,554	18,231
575			83,696	18,837
600	251,9	32,2	88,921	19,431
625			94,22	20,013
700	280,9	35,9		