PL Engineering Ltd.

TEC EXPERT DX8020

User Guide

Moscow, 2022

version 2.01

WARRANTY

PL ENGINEERING LTD warrants that the TEC Expert DX8020, if properly used and installed, will be free from defects in material and workmanship and will substantially conform to PL ENGINEERING's publicly available specification for a period of one (1) year after date of the TEC Expert DX8020 was purchased.

PL ENGINEERING LTD also provides a 3-month warranty for the following parts and components included in the standard delivery set of the product: the cables, program disks and documentation

If the TEC Expert fails during the warranty period PL ENGINEERING will repair the TEC Expert or replace it or its parts.

For the warranty support a Consumer can address to the office of the company PL ENGINEERING or its sales representative.

The product repaired or replaced in whole or in part, will have the warranty period counted as one (1) year from initial shipment but not less than 3 months upon shipping of repair or replacement.

TECHNICAL SUPPORT

For the technical support and repair within and after the warranty period, please, address:

In Russia and CIS

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Fax: +7-499-678-3258
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e-mail: info@tec-microsystems.com

CONTENTS

1. INTRODUCTION

The User's Guide is to provide thorough information for studying and handling the TEC Expert model DX8020 (for brevity further can be referred to as the DX8020).

It is only the personnel acquainted with all the sections of this guide who can operate the facilities.

The DX8020 is meant for measuring parameters of thermoelectric (TE) single-stage and multistage modules – Table 1.

Table 1

Measured Parameter	Designation	Notes
TE module temperature difference versus electric current at zero heat load $Q = 0$	$\Delta T = f(I)$	Direct measurements
TE module maximum temperature difference at zero heat load $Q = 0$	ΔT_{max}	
Electric current at which ΔT_{max} is achieved	I_{max}	
TE module electric voltage versus electric current at zero heat load	$U = f(I)$	
Electric voltage at which ΔT_{max} is achieved	U_{max}	
TE module temperature difference versus heat load available at electric current fixed	$Q = f(\Delta T)$	
Maximum heat load capacity at $I_{max}(\Delta T = 0)$	Q_{max}	
TE module Figure-of-Merit	Z	Z-metering
TE module electric resistance	R	
TE module time constant at $0.01 I_{max}$	τ	
Average Seebeck coefficient of TE material	α	
Average electric conductivity of TE material	σ	

The TEC Expert DX8020 provides capability to measure complete performance specifications of a TE module at one measuring cycle.

The DX8020 is intended for acceptance, qualification and research testing of TE modules.

2. SPECIFICATIONS

2.1. TE module parameters

The ranges of the parameters of single- and multistage TE modules measured by DX8020 are given in Table 2.

Table 2

Measured parameter	Designation	Units	Range	Accuracy
Temperature	T	ºC	-120…+85	±0.3 ºC
Maximum temperature difference	ΔT_{max}	ºC	0…140	±0.3 ºC
TE module electric current	I	A	0…6	±3 mA
TE module electric voltage	U	V	0…16	±3 mV
Maximum heat load	Q_{max}	W	20	
Maximum electric power	P_{max}	W	30	
AC electric resistance	AC R	Ohm	0…100	0.6 % *but not better than 0.01 Ohm*
TE module Figure-of-Merit	Z	1000/K	0…4	1.5 %
Time constant	τ	s	0…10	1.5 %
Average Seebeck coefficient	α	µV/K	100…300	10 %
Average electric conductivity	σ	1/Ohm*cm	400…2500	10 %

2.2. Maximal performance

Table 3

Parameter	Designation	Units	Range	Accuracy
Tested TE module max dimensions	CxD	mm²	30x30	
Tested TE module max height	H	mm	30	
Tested TE module heat load	Q	W	0…6	0.005
Additional heat load on a stage of a multistage TE module	Q_{add}	W	0…6	0.005
Maximum heat rejection	Q_{hot}	W	0…40	
Thermostabilizing TE module base surface temperature	T_{hot}	ºC	-10…85	0.2
Minimum temperature increment	δT_{hot}	ºC	1	0.2
Tested TE module electric current	I	A	0…6	
Minimum electric current increment	ΔI	A	0.002	
Time of temperature stabilizing	t		10 s … 30 min	
Vacuum	P	mm Hg	< 1x10^{-2}	

2.3. Power consumption

The DX8020 is meant for laboratory measurements at the ambient temperature 25±4ºC and relative humidity up to 80%.

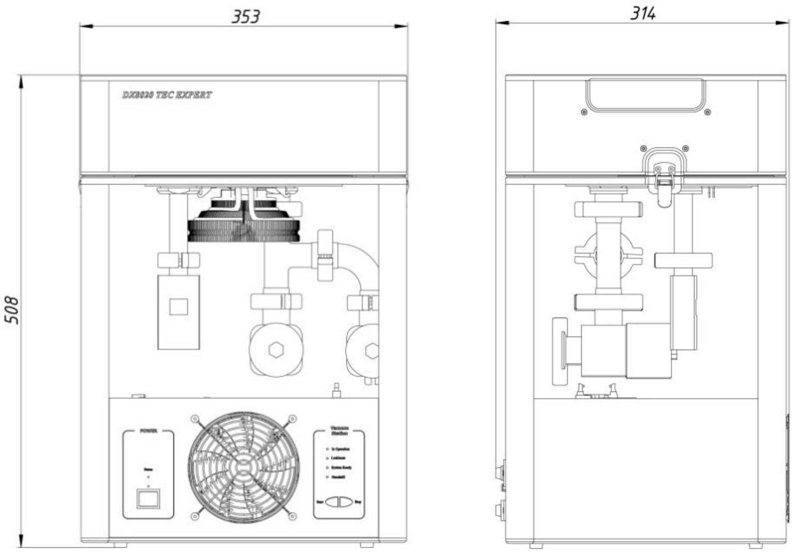
- AC voltage: - 220 +10/-15 V;
- Power consumption: not exceeding 500 W.

2.4. Dimensions

2.4.1. Main Block

Dimensions – 353 x 314 x 508 mm³.

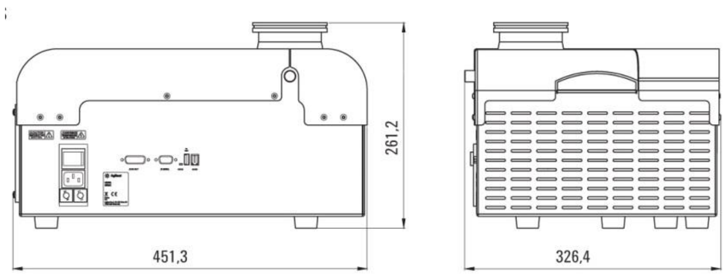
Weight - 20,0 kg.



2.4.2. Vacuum station

Dimensions* – 451,3 x 326,4 x 261,2 mm³.

Weight - 16,7 kg.



* Model Agilent TPS-compact X3580A

3. DELIVERY KIT

Main block DX8020.

Vacuum station with turbo molecular pump.

* Vacuum station model, may differ from shown in the picture.

Power cable.

Power cable for vacuum station.

RS232 cable.

	Flex Vacuum pipe (1m or 1.2m long).
	Vacuum Interconnector.
	Sealing ring (large)
	Fixture clamps. 4 pcs.
	Clamps. 2 pcs.
	Sealing rings (small). 2 pcs.
	Package with installation parts for mounting samples.

Silicone vaseline.

4. DESCRIPTION

4.1. System Arrangement

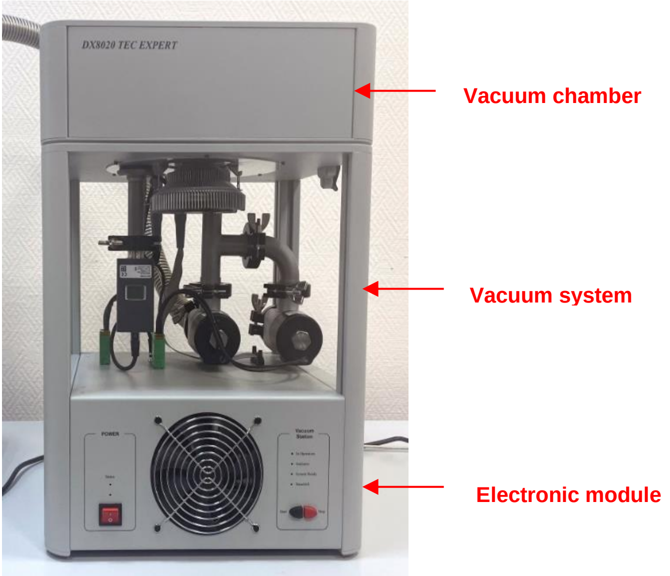
The DX8020 TEC Expert consists of two units - the Main block and the Vacuum station.

They are interconnected by a vacuum pipeline and a power cable for switching on the Vacuum station from the Main block.

4.2. Main Block

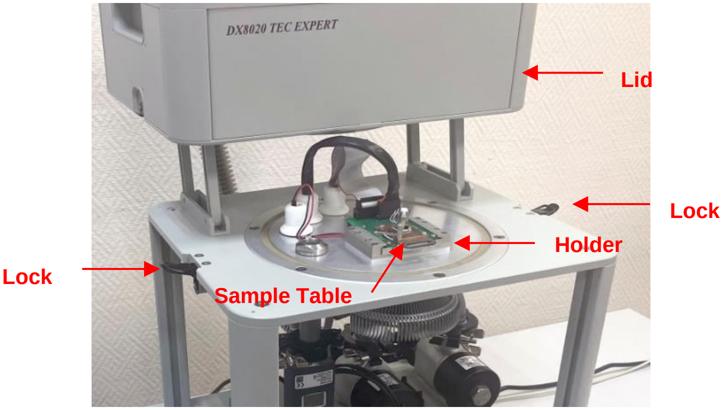
The Main measuring block consists of three parts:

- ✓ Vacuum chamber for samples.
- ✓ Vacuum system.
- ✓ Electronic control module.



4.2.1. Vacuum chamber

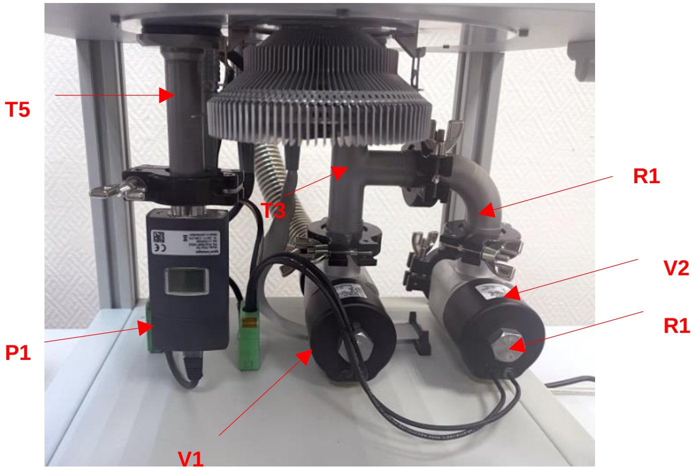
The vacuum chamber of the sample is covered with a lid with a lifting mechanism and locks. In the vacuum chamber there is a sample holder and cable connectors for connecting the sample table (removable) to the control electronics.

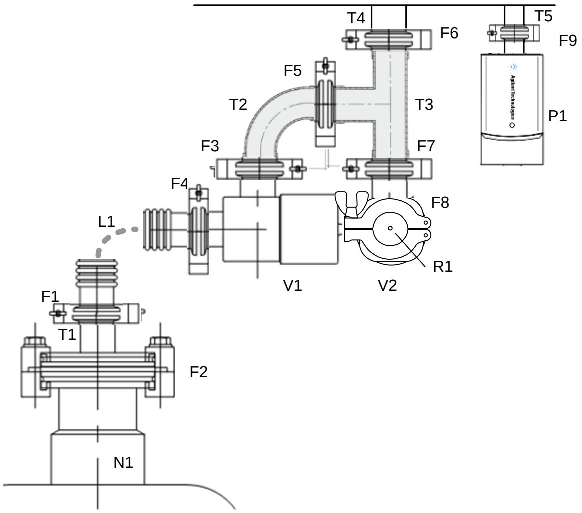


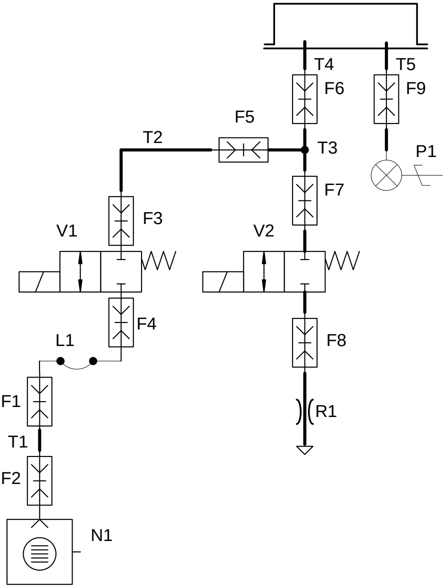
4.2.2. *Vacuum system*

A diagram of the vacuum system is shown in the figures and photos below.

The vacuum system includes connecting pipelines (T1-T8) with vacuum seals (F3-F9). Two solenoid locking valves (V1, V2). One (V1) on the suction line of the vacuum system, the second (V2) on the air intake line. Vacuum gauge Pirani (P1) for measuring the vacuum in the sample chamber.




T4
T5
F6
F9
F5
T2
T3
P1
F3
F7
F4
F8
L1
R1
V1
V2
F1
T1
F2
N1


T4
T5
F6
F9
F5
T2
T3
P1
F7
F3
V1
V2
F4
L1
F8
F1
R1
T1
F2
N1

4.2.3. Electronic module

The electronics module is located at the bottom of main block.

On the front side there is a power switch and buttons for turning on and off the vacuum pump.

LEDs display the status of working.

4.3. Vacuum pump

The DX8020 TEC Expert is equipped with a compact vacuum station with a turbomolecular pump.

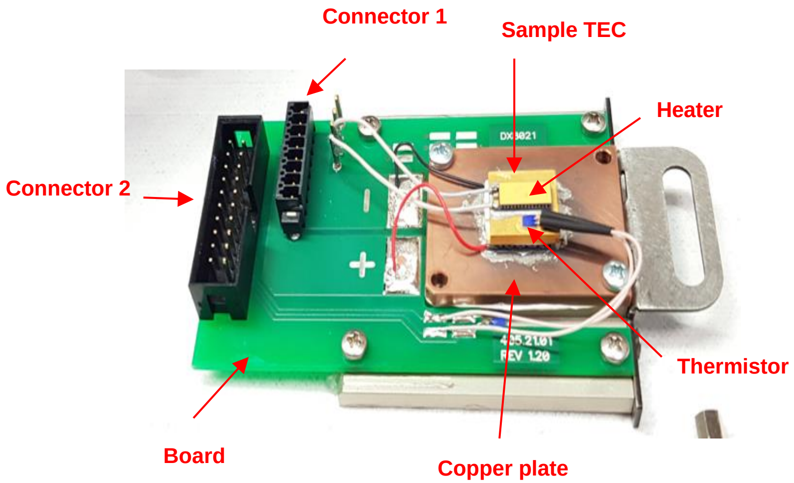
The model of the vacuum station may differ from the one shown in the figure.

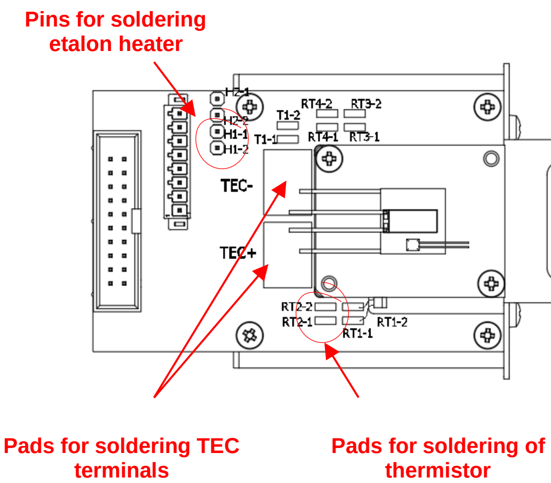
4.4. Test sample

The delivery set of DX8020 TEC Expert includes a ready-made test sample TEC mounted on the sample table and ready for measurement.

We recommend that you use this test sample to train users during the installation evaluation phase.

The procedure for preparing the Test sample is described in detail in a separate document – “DX8020 Sample Preparation Instruction”.


Connector 1
Sample TEC
Heater
Connector 2
Thermistor
Board
Copper plate


Pins for soldering etalon heater
H2-1
H2-2
H1-1
H1-2
T1-2
T1-1
RT4-2
RT3-2
RT4-1
RT3-1
TEC-
TEC+
RT2-2
RT2-1
RT1-1
RT1-2
Pads for soldering TEC terminals
Pads for soldering of thermistor

5. DEVICE INSTALLATION

Detailed instructions on how to connect the installation are set out in a separate document.

Briefly, the order is as follows

5.1. Preparations

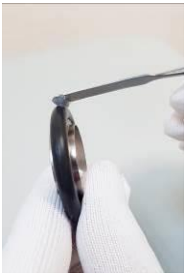
Take of main block, vacuum station, and parts from delivery package.

Remove packages.

Situate main block on a table and vacuum station near it

Remove plastic covers from flanges of vacuum pipeline, Interconnector, and vacuum pump.

Lubricate sealing rings (big and small ones) with a small amount of Silicone Vaseline. Wipe off silicone vaseline residue with a lint-free cloth.



Put the lubricated rings on dry and clear surface after this.

5.2. Assembling of vacuum system

Plastic cover must be removed from vacuum station flange before installations

Put big vacuum seal ring

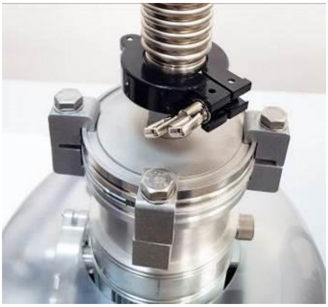
Put vacuum interconnector

Mount interconnector with use of four vacuum fixtures.

The bolts should be tightened evenly (sequentially in several passes) without misaligning the interconnector.

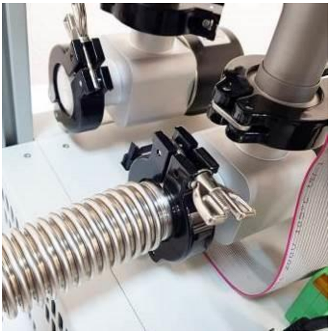
Put small vacuum seal ring.

Connect vacuum pipe flange.



Fix vacuum pipe with use of vacuum clamp.

Put small vacuum seal ring to vacuum valve in main block. Connect other side of vacuum pipe to Valve flange.



Fix vacuum pipe with use of vacuum clamp.

5.3. Electric connections


Connect Vacuum Station to Main Block by Vacuum Station Power cable.

* Switch at the station must be in the position ON always.


Connect Main Block to power supply by Electronic Block Power cable.

Connect RS232 cable (male) to Electronic Block connector, marked "RS232".

another end of the cable (female) connect to PC.

The DX8020 TEC Expert system is completed.

5.4. Check of vacuum system

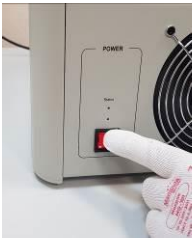
The lid of the working vacuum chamber must be closed and fixed with locks.

Power button on vacuum station must be ON.

* must be always ON.

Make sure the system venting plug is closed.

* must be always closed.



Switch on power button on main block.

LED In Operation blink.

Switch on Start button on Vacuum Station frame. Vacuum station starts working.

LED In Operation light.

* The operation of the turbomolecular pump can be determined by the characteristic high-frequency sound.

Look at the vacuum gauge.

Pressure in vacuum systems goes down quickly.

According to the indication of the vacuum meter, the pressure should drop below $7*10^{-3}$ Torr.

LED System Ready light.

Press Stop button in Vacuum Station frame and wait several seconds. Vacuum station stops working.

LED Standstill will blink.

After that, the vacuum valve is triggered (characteristic click will be heard). Pressure will be atmospheric.

LED Standstill will light. For several minutes, the station cannot be started again so that it does not break.

When LED In Operation starts flashing again, the station can be started again.

6. MAINTENANCE

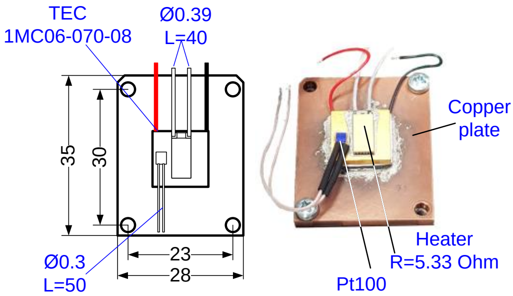
1) Perform the following monthly maintenance:
   - wipe the vacuum table with ethyl alcohol.
   - clear the fan ribs of dust by a vacuum cleaner.
2) When in operation do not bar the vent-holes of the TEC Expert DX8020 Main block.

7. SAMPLE PREPARATIONS

The preparation of samples for measurement is described in detail in a separate document - «DX8020 Sample Preparation Instruction».

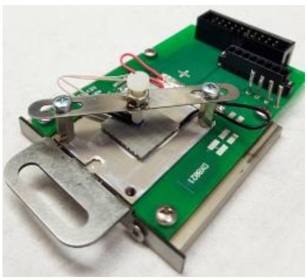
There are several ways to prepare samples for measurement.

A. First, DX8020 TEC Expert is supplied by the manufacturer with a Test sample pre-installed on the sample table in a vacuum chamber. The test sample is designed to train the unit and perform test measurements. The Test sample is ready for complex measurements in all modes of the device.



B. Most complex investigations mean measurements of cooling capacity ΔT and cooling power Q or sample TEC. In the case testing TEC samples must be equipped with reference thermistor and reference heater on cold side.

C. Very often it is necessary to investigate only cooling capacity – ΔT. Without measurements of cooling power Q. It is simplified experiment, means simpler preparations of TEC sample – without mounting of etalon heater.



8. OPERATION PROGRAM

8.1. System Requirements

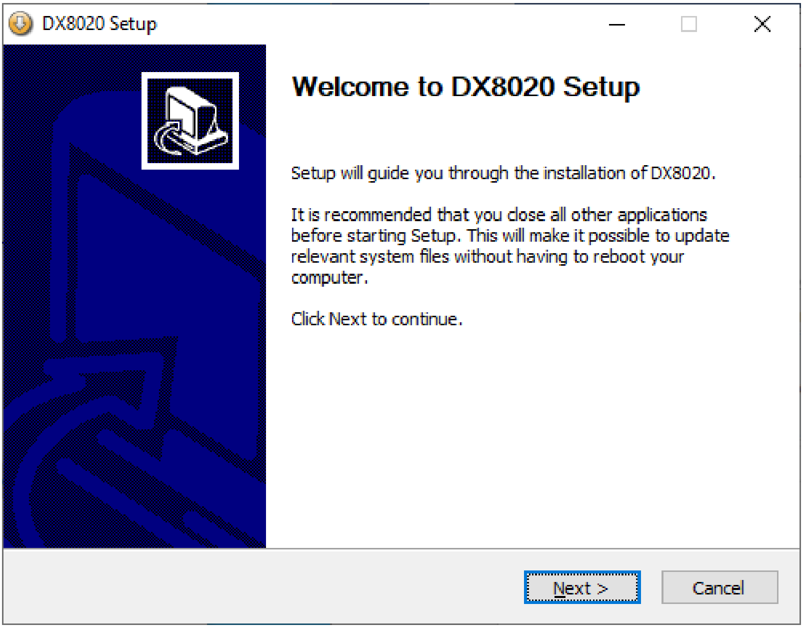
The DX8020 software allows all the necessary interaction with the device DX8020. To work with the program, one must be of minimal knowledge of working with MS Windows operating system.

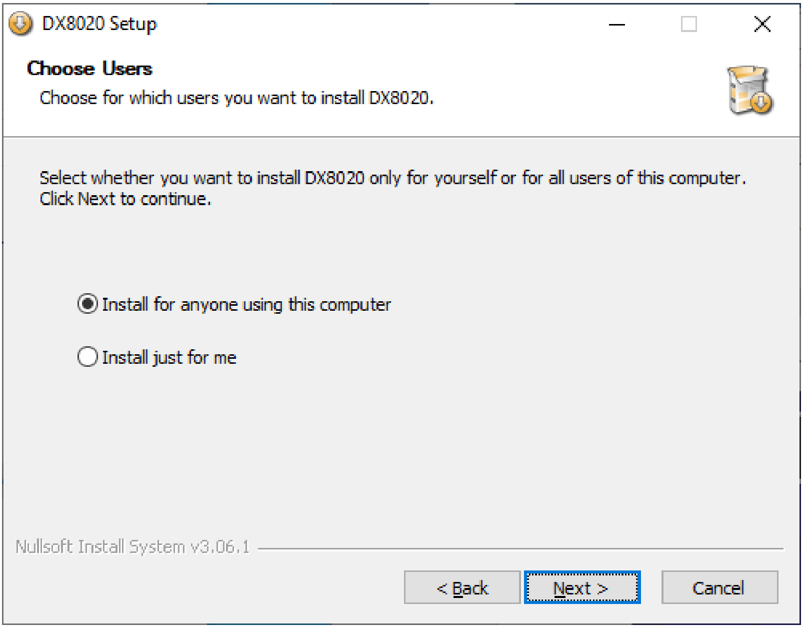
Computer must have free serial port.

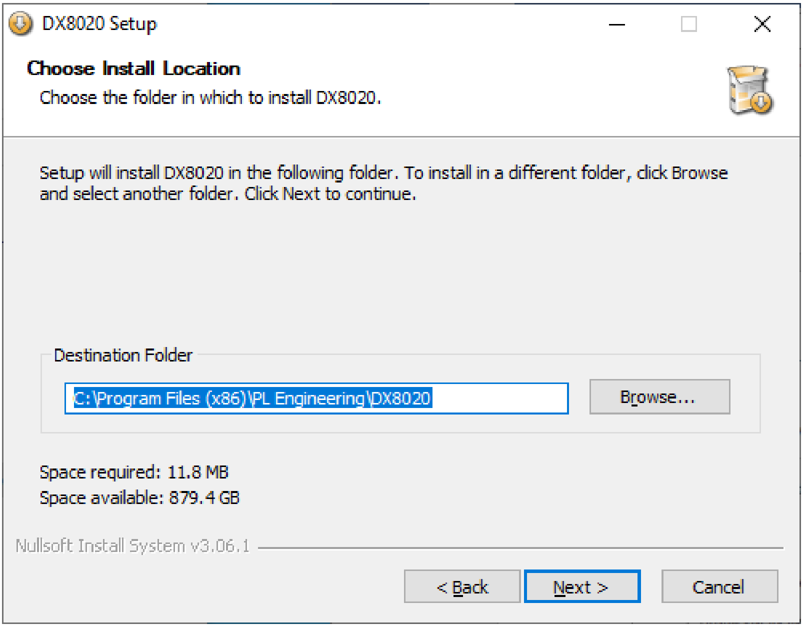
8.2. Program Installation

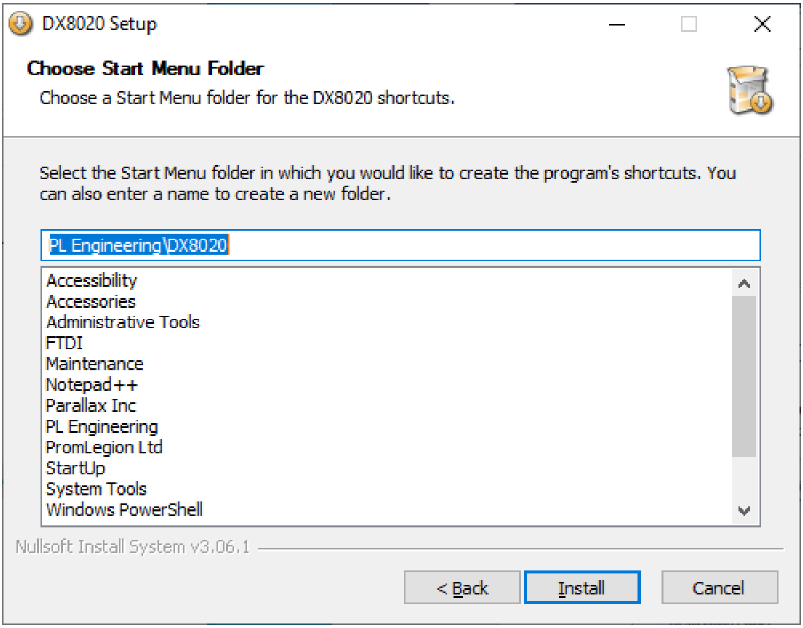
Download installation program DX8020 Setup.exe from USB disc of from the manufacturer website https://promln.ru/docs/

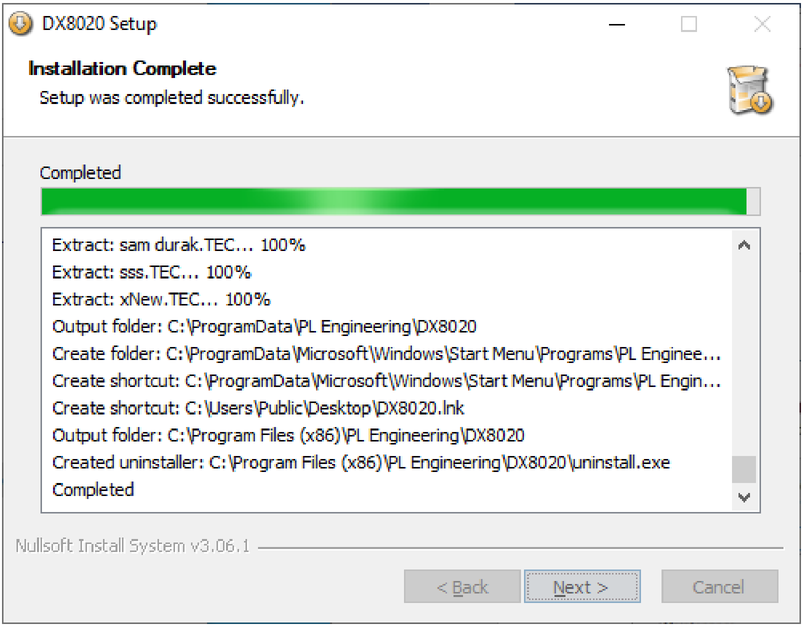
Start the installation exe file and follow corresponding instructions during installation procedure.

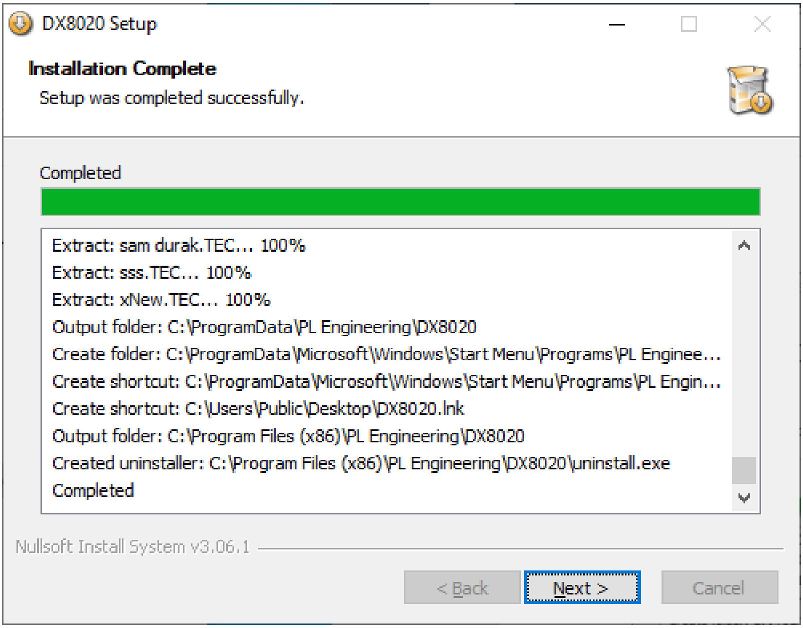


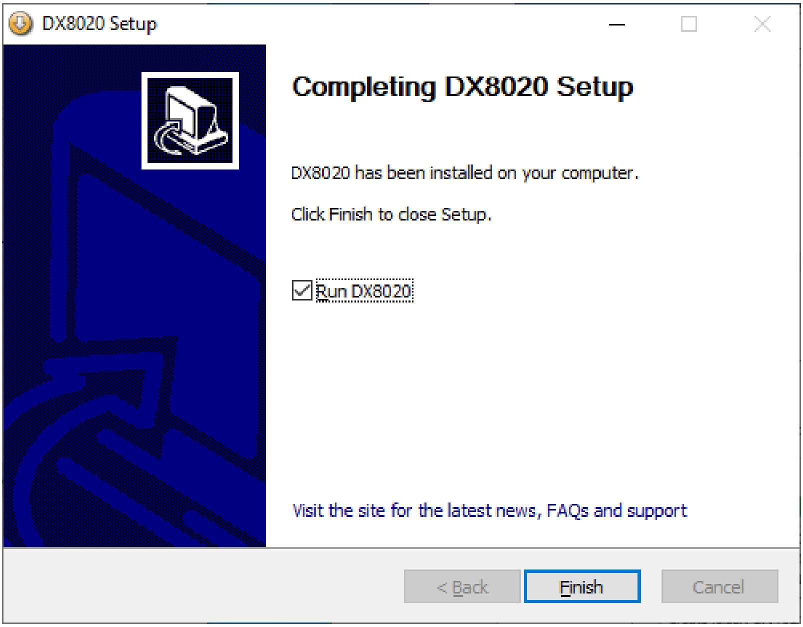

DX8020 Setup
Choose Users
Choose for which users you want to install DX8020.
Select whether you want to install DX8020 only for yourself or for all users of this computer. Click Next to continue.
Install for anyone using this computer
Install just for me
Nullsoft Install System v3.06.1
< Back
Next >
Cancel


DX8020 Setup
Choose Install Location
Choose the folder in which to install DX8020.
Setup will install DX8020 in the following folder. To install in a different folder, click Browse and select another folder. Click Next to continue.
Destination Folder
C:\Program Files (x86)\PL Engineering\DX8020
Browse...
Space required: 11.8 MB
Space available: 879.4 GB
Nullsoft Install System v3.06.1
< Back
Next >
Cancel


DX8020 Setup
Choose Start Menu Folder
Choose a Start Menu folder for the DX8020 shortcuts.
Select the Start Menu folder in which you would like to create the program's shortcuts. You can also enter a name to create a new folder.
PL Engineering\DX8020
Accessibility
Accessories
Administrative Tools
FTDI
Maintenance
Notepad++
Parallax Inc
PL Engineering
PromLegion Ltd
StartUp
System Tools
Windows PowerShell
Nullsoft Install System v3.06.1
< Back
Install
Cancel


DX8020 Setup
Installation Complete
Setup was completed successfully.
Completed
Extract: sam durak.TEC... 100%
Extract: sss.TEC... 100%
Extract: xNew.TEC... 100%
Output folder: C:\ProgramData\PL Engineering\DX8020
Create folder: C:\ProgramData\Microsoft\Windows\Start Menu\Programs\PL Enginee...
Create shortcut: C:\ProgramData\Microsoft\Windows\Start Menu\Programs\PL Engin...
Create shortcut: C:\Users\Public\Desktop\DX8020.lnk
Output folder: C:\Program Files (x86)\PL Engineering\DX8020
Created uninstaller: C:\Program Files (x86)\PL Engineering\DX8020\uninstall.exe
Completed
Nullsoft Install System v3.06.1
< Back
Next >
Cancel


DX8020 Setup
Installation Complete
Setup was completed successfully.
Completed
Extract: sam durak.TEC... 100%
Extract: sss.TEC... 100%
Extract: xNew.TEC... 100%
Output folder: C:\ProgramData\PL Engineering\DX8020
Create folder: C:\ProgramData\Microsoft\Windows\Start Menu\Programs\PL Enginee...
Create shortcut: C:\ProgramData\Microsoft\Windows\Start Menu\Programs\PL Engin...
Create shortcut: C:\Users\Public\Desktop\DX8020.lnk
Output folder: C:\Program Files (x86)\PL Engineering\DX8020
Created uninstaller: C:\Program Files (x86)\PL Engineering\DX8020\uninstall.exe
Completed
Nullsoft Install System v3.06.1
< Back
Next >
Cancel

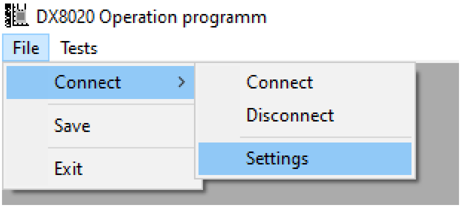

DX8020 Setup
Completing DX8020 Setup
DX8020 has been installed on your computer.
Click Finish to close Setup.
Run DX8020
Visit the site for the latest news, FAQs and support
< Back
Finish
Cancel

Follow all the installation steps. When the installation is over, the program icon will appear on the desktop and in the "Start" menu.

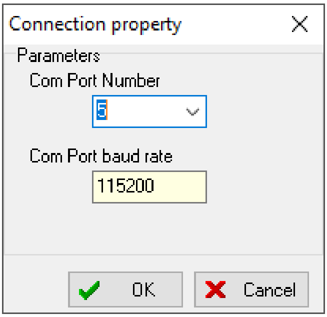
8.3. Connection

To connect with the device, it is necessary:

- connect the device DX8020 and computer by the interface cable.
- start program DX8020 Operation program
- select the menu item "Main Menu" > "File" > "Connect" > "Settings".



- In the resulting window, select the port you are connecting to, and set baud rate 115200.



- select the menu item "Main Menu" > "File" > "Connect" > "Connect".

If the connection is successful, the status says "DX8020 ver. xxx found at selected COM port".

If the connection fails, the message of an unsuccessful attempt to connect to the device appears.

To solve this problem, follow these:

- Check the connection of the device with your computer.
- Check the power supply unit.
- Turn off and on the device.
- Restart the software;
- If nothing helps, contact technical support.

8.4. Disconnection

To disconnect, select the menu item "Main Menu" > "File" > "Connect" > "Disconnect".

8.5. Main Window

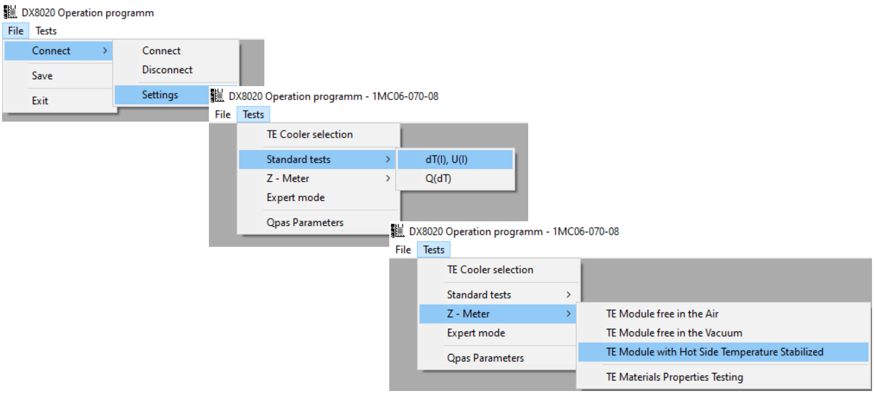
After starting the program, the software main window depicted in the figure appears.

The main window can be divided into three fields.

- Main menu.
- Temperature sensors panel.
- Status bar.

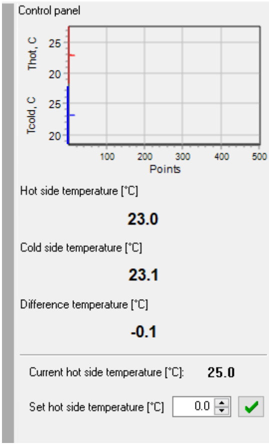
8.5.1. *Main Menu*

The main menu structure is shown below.



8.5.2. Temperature sensors panel

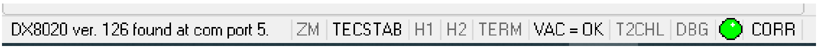
Temperature sensors panel is located in the right-hand part of the main window.



The telemetry data from the sensors "T_1" (Hot side temperature) and "T_2" (Cold side temperature), as well as the difference temperature between the two sides is displayed.

To set the hot side temperature is only available at a testing mode selected.

Status Panel



This panel is intended for the output of:

- device identification;
- device mode;
- temperature stabilization status;
- vacuum status;
- corrections status.

8.6. TE Module Selection from the Database

The software contains default database of the manufacturer of the DX8020 TEC Expert device.

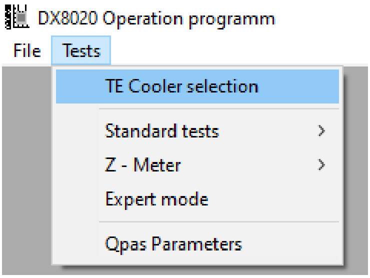
The nomenclature of these TECs is available from websites:

https://promln.ru/products/tem/

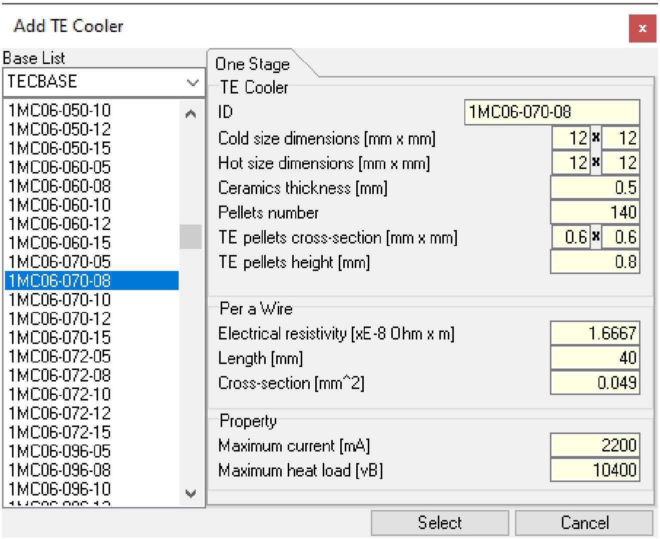
https://www.tec-microsystems.com/products/thermoelectric-coolers/index.html.

Here in the database the nomenclature of TECs is included with detailed parameters of design.

To select a TE module from the database, choose from the Main Menu the item "Main Menu" > "Tests" > "TE Cooler selection".



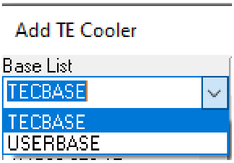
The following window will be displayed:



By default, a list of TE modules is displayed. For a TE module selected, in the right-hand window part one can see its specification involved.

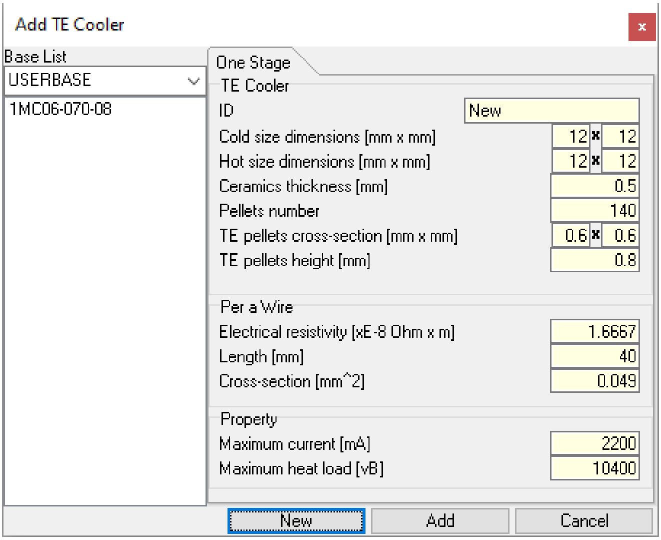
8.7. New TE module introduction

To add new TE module, it is necessary to choose "USERBASE" from combo box.



Then press the button "New".

You are supposed to input the values of parameters required and save the new TE module specification pressing the button "Add".



It is possible to proceed with measurements without identifying the TE module to be tested (except the mode "TE Materials Properties Testing"). In this case no corrections will be calculated.

8.8. Experiment arrangement setting

For correct and accurate measurements of cooling performance and particularly cooling power it is very important experiment arrangement, namely parasitic heat loads to testing TEC cold side.

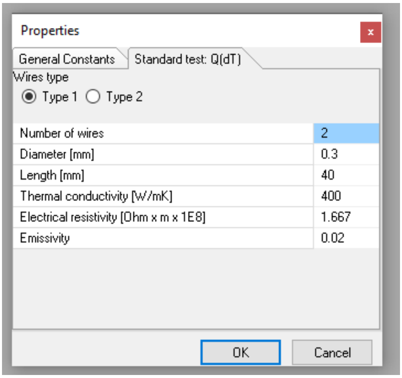
These parasitic loads are provided by connecting wires of thermistor and etalon heater mounted to the testing TEC cold side.

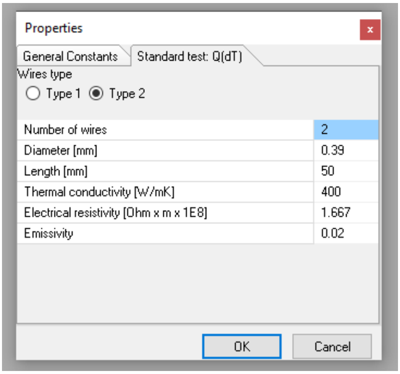
Select "Main Menu" > "Tests" > "Qpas Parameters" >" Standard test: Q(dT)"

And set parameters of terminal wires

Type 1 – wires of thermistor

Type 2 – wires of etalon heater





9. MEASURING METHODS

In addition to this key section of the Manual, to help the user, we have prepared a separate document "DX8020 How to Get Started", which gives step-by-step instructions on how to take various measurements using the device TEC Expert DX8020.

This instruction is available on the following websites:

https://promln.ru/docs/

https://www.tec-microsystems.com/downloads.html

9.1. Summary

The TEC Expert DX8020 provides the following testing modes:

1. STANDARD: testing TE module standard performance plots in vacuum

   1.1 At the zero heat load within electric current range: $\Delta T(I)$, $U(I)$;

   1.2 At varied heat load at a certain electric current: $Q(\Delta T)$

2. EXPERT: testing of a TE module parameters in the given operational point (given operating current, heat load and stabilizing temperature).

3. $Z-R-\tau$ Metering

   3.1 TE module is free in the ambient:

      3.1.1 The ambient is air.

      3.1.2 The ambient is vacuum.

   3.2 TE module hot side temperature is stabilized (vacuum)

4. TE Materials PROPERTIES in a TE module (vacuum)

Before the measurements, select the type of the module tested.

9.2. Standard Mode

The major task of the standard measurements is to measure Standard Performance Plots and to confirm the tested TE module standard specifications, i.e., the following parameters: ΔT_{max}, Q_{max}, I_{max}, U_{max} in vacuum. The tested TE module hot side temperature T_{hot} can be fixed within the range available (Table).

The characteristics measured in this mode are:

- $\Delta T(I)$ – temperature difference dependent on electric current at the cooling capacity $Q=0$. *The plot is used to obtain I_{max} and ΔT_{max} of a TE module.*
- $U(I)$ – volt-ampere characteristics at the cooling capacity $Q=0$. *The plot is used to obtain U_{max}.*
- $Q(\Delta T)$ – temperature difference versus cooling capacity $\Delta T(Q,I)$ and voltage versus temperature difference $U(\Delta T,I)$ at a certain current up to I_{max}. *The results are Q_{max} and ΔT_{max} at the current chosen.*

The testing conditions are as follows.

1) A base with a heater and a thermal resistance is mounted onto the TE module cold side (see Section 7).
2) The TE module hot side is mounted onto the sample holder mounting surface (see Section 7).

3) The TE module leading wires are soldered to the connecting plates according to the TE module polarity.

4) The thermostabilizing module is switched on. The temperature $\boldsymbol{T_{hot}}$ of the thermostabilizing surface is fixed within the range available (see Table).

5) The cover is closed;

6) The vacuum chamber is pumped out to pressure of residual gases not exceeding $1 \cdot 10^{-2}$ mm Hg.

9.2.1. Measurement of *ΔT(I), U(I) at Q=0*

This mode is to enable building the dependences of the TE module temperature difference ΔT and the voltage U on electric current I, as well as obtaining the values $\Delta T_{max}(I_{max})$, U_{max}, I_{max} – see "*Annex VI*. Measurement of I_{max}, ΔT_{max}"

The additional requirement: the heater is off.

The testing procedure in the automatic mode is as follows:

1) Set the required temperature of the thermostabilized surface $\boldsymbol{T_{hot}}$.

2) Choose the TE module stabilization time $\boldsymbol{t_{stab}}$ and wait until the base temperature is steady.

3) Set the limiting testing electric current values (see *Annex VI*. Measurement of $\boldsymbol{I_{max}}$, $\Delta \boldsymbol{T_{max}}$).

4) Set the electric current step.

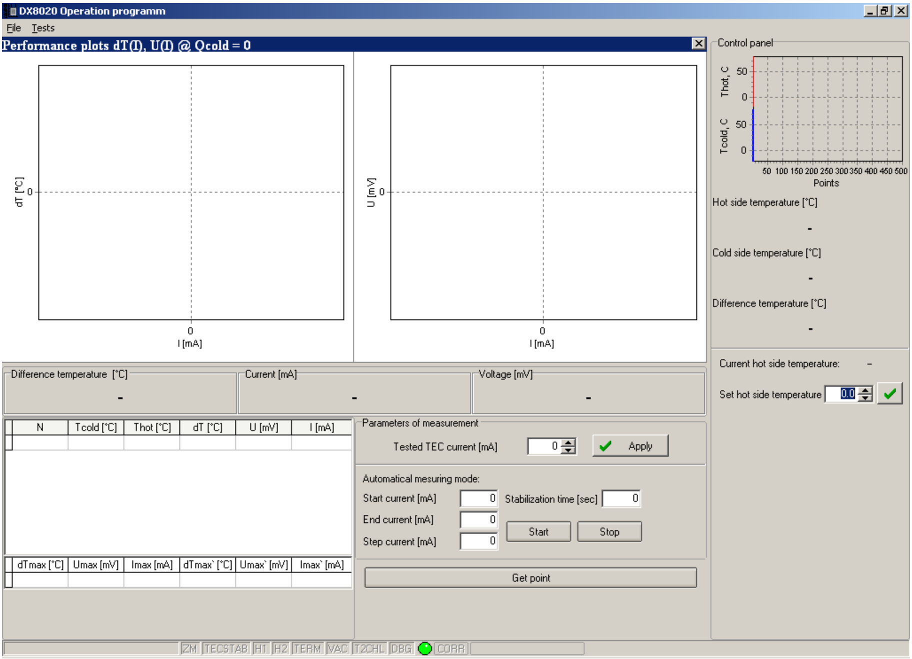
5) Start measuring. Consistently the TE module is fed by a constant electric current, beginning from $\Delta \boldsymbol{I}$, TE module is maintained at a given current during $\boldsymbol{t_{stab}}$ to achieve steady-state.

6) For each electric current value $\boldsymbol{I}$ the TE module temperature difference $\Delta \boldsymbol{T}(\boldsymbol{I})$ and voltage $\boldsymbol{U}(\boldsymbol{I})$ are captured: in a steady state the following parameters are registered: TE module electric current, voltage drop, the base temperature; temperature difference between the base and TE module cold surface.

7) 8) The data $\Delta T(I)$ are processed; the values I_{max}, U_{max}, ΔT_{max} are calculated with no corrections applied (see "*Annex VI*. Measurement of I_{max}, ΔT_{max}").

To enter this mode of measurement, you must select "Main Menu" > "Tests" > "Standard tests" > "$dT(I)$, $U(I)$". The window of measurements looks as shown below.

It should be noted that after starting measurements the thermal stabilization of the base is done in accordance with set. The temperature of the set point can be changed "Set hot side temperature".



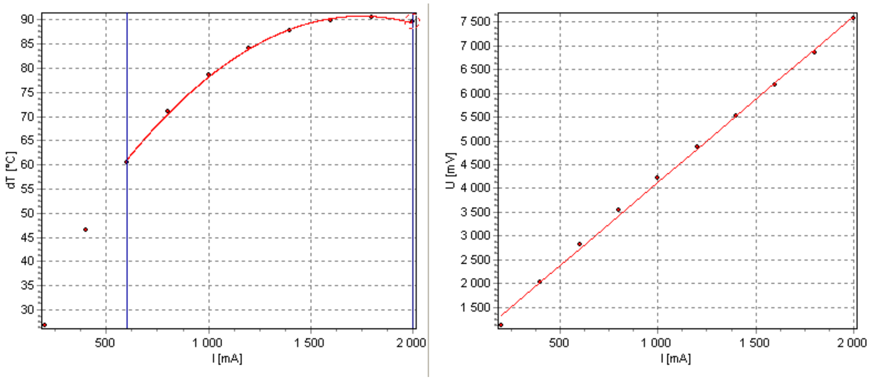
The window is divided into several fields.

- Field of plots $dT(I)$ and $U(I)$;
- Field of current values dT, I, U;

- Table of measured points;
- Control Panel.

Field of plots $dT(I)$ and $U(I)$

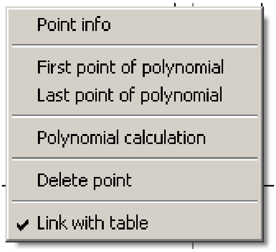
Field of plots $dT(I)$ and $U(I)$ is shown below.



The graphs depict the points measured. If indicating by the mouse to a point on the plot, the values and parameters of this point are highlighted by the red color in the summary table.

[illegible]	[illegible]	27.1	[illegible]	[illegible]	[illegible]
10	-62.6	27.1	89.7	7572	2000

Mistaken and unnecessary points can be deleted. To do it just approach the point you want to delete by the mouse cursor until it is enclosed in the red circle. Press the right button of the mouse to obtain the context menu.



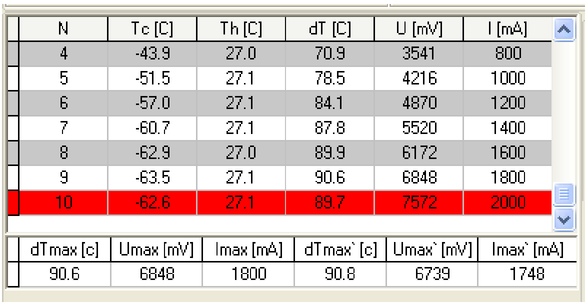
Choose "Delete point".

Field of current values dT, I, U

This field displays current values dT, I, U of the tested TE module. In the manual mode with the help of these values it is possible to estimated if the module is stabilized or not.

Table of Measured Points

This table contains the measured values as well as the value of the electric current. The bottom line summarizes the measured values dT_{max}, U_{max}, I_{max} and the values dT_{max}, U_{max}, I_{max} calculated by a polynomial.



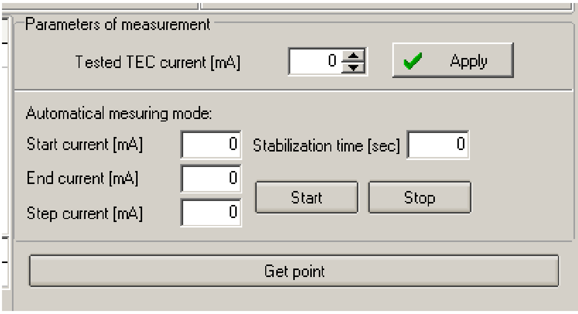
N	Tc [C]	Th [C]	dT [C]	U [mV]	I [mA]
4	-43.9	27.0	70.9	3541	800
5	-51.5	27.1	78.5	4216	1000
6	-57.0	27.1	84.1	4870	1200
7	-60.7	27.1	87.8	5520	1400
8	-62.9	27.0	89.9	6172	1600
9	-63.5	27.1	90.6	6848	1800
10	-62.6	27.1	89.7	7572	2000

dTmax [c]	Umax [mV]	Imax [mA]	dTmax` [c]	Umax` [mV]	Imax` [mA]
90.6	6848	1800	90.8	6739	1748

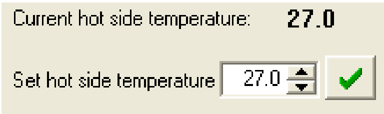
The red-colored line corresponds to the point indicated by the mouse.

Control Panel

This field allows control of the testing procedure.



Before starting the test, it is necessary to set the temperature of the stabilizing basement and wait some time to achieve the stabilization.



The test can be done either manually or automatically.

Testing Manually

Set the electric current value and click "apply".

After achieving a steady-state temperature of the module cold side press the button "Get point".

Testing Automatically

It is necessary to set the starting and finishing values of the electric current the TE module is to be tested at, the electric current step and the hot side stabilization time.

To start the measuring cycle, press the button "Start". The data will be taken automatically within the settings given.

After the test is over, a square-law polynomial is built by all the measured points. The measured values dT_{max}, U_{max}, I_{max} and the values dT_{max}, U_{max}, I_{max} extracted from the polynomial are displayed.

If needed, it is possible to set limiting current values for the polynomial. To do it you are to choose a point, click the right button on the mouse; select "First Point of polynomial" or "Last Point of polynomial" from the context menu. By narrowing the interval of polynomial, the values dT_{max}, U_{max}, I_{max} can be obtained more exactly.

9.2.2. Measurement of Q(ΔT)

This mode is intended for obtaining the dependence of the TE module heat load Q on the module temperature difference dT at the given electric current I, as well as for calculating the maximum heat to be pumped Q_{max} and extracting the corrected value dT_{max} at the given current (see *Annex VII*. $\boldsymbol{Qmax}$ Measurement.$\Delta\boldsymbol{T}\boldsymbol{max}$ Correction).

The additional requirement in this option: the heater is off.

The testing procedure is as follows.

1) Set the required temperature of the thermostabilized surface $\boldsymbol{T_{hot}}$.

2) Choose the TE module stabilization time $\boldsymbol{t_{stab}}$ and wait until the base temperature is steady.

3) Set the current I through the TE module. To measure the specification value Q_{max}, the condition is $I = I_{max}$, where I_{max} is obtained either during the measurements (see Measurement of $\mathrm{T(I), U(I)}$ at $\mathrm{Q = 0}$), either by calculation.

4) For the automatic testing define the upper limit of the heat to be loaded $\boldsymbol{Q_{lim}}$ at the electric current selected. We recommend:

$$Q_{lim} = \frac{1}{2} Q_{max}, \qquad (9.1)$$

where Q_{max} *- TE module maximum cooling capacity estimated by calculations at the chosen current.*

5) At the given current the TE module temperature difference $\Delta \boldsymbol{T}$ is measured for 5 values of the heater power: $\boldsymbol{Q} = (\mathbf{0}, \mathbf{0.25}, \mathbf{0.5}, \mathbf{0.75}, \mathbf{1.0})\boldsymbol{Q_{lim}}$. For each measurement the TE module stabilization time is $\boldsymbol{t_{stab}}$.

6) Build the curve $\boldsymbol{Q}(\Delta \boldsymbol{T})$ by the measured points using linear interpolation (*See Annex VII.* $\boldsymbol{Q_{max}}$ Measurement.$\Delta \boldsymbol{T}$ $\boldsymbol{max}$ Correction).

7) For each measured $\Delta \boldsymbol{T}$ at the given current I the correction for the passive heat load from the wires is calculated:

$$Q_{pass}(\Delta T) = Q_{wire}(\Delta T) \qquad (9.2)$$

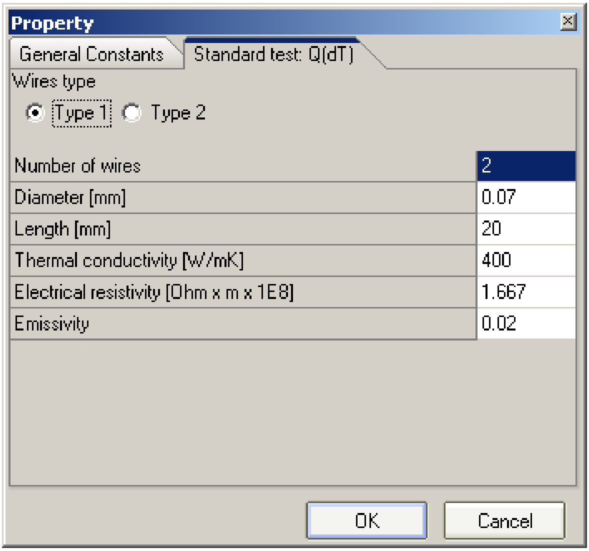
(see “*Annex IV.* Heat Flux along Leading Wires”).

8) The new curve is built $\boldsymbol{Q}'(\Delta \boldsymbol{T}) = \boldsymbol{Q}(\Delta \boldsymbol{T}) + \boldsymbol{Q_{pass}}(\Delta \boldsymbol{T})$.

9) Find $\boldsymbol{Q_{max}}$, $\Delta \boldsymbol{T_{max}}$ at a given current (see *Annex VII*. $\boldsymbol{Q_{max}}$ Measurement and $\Delta \boldsymbol{T_{max}}$ Correction)

10) Find $\boldsymbol{Q'_{max}}$, $\boldsymbol{\Delta T'_{max}}$ at a given current (see Annex VII. $\boldsymbol{Q_{max}}$ Measurement and $\boldsymbol{\Delta T_{max}}$ Correction).

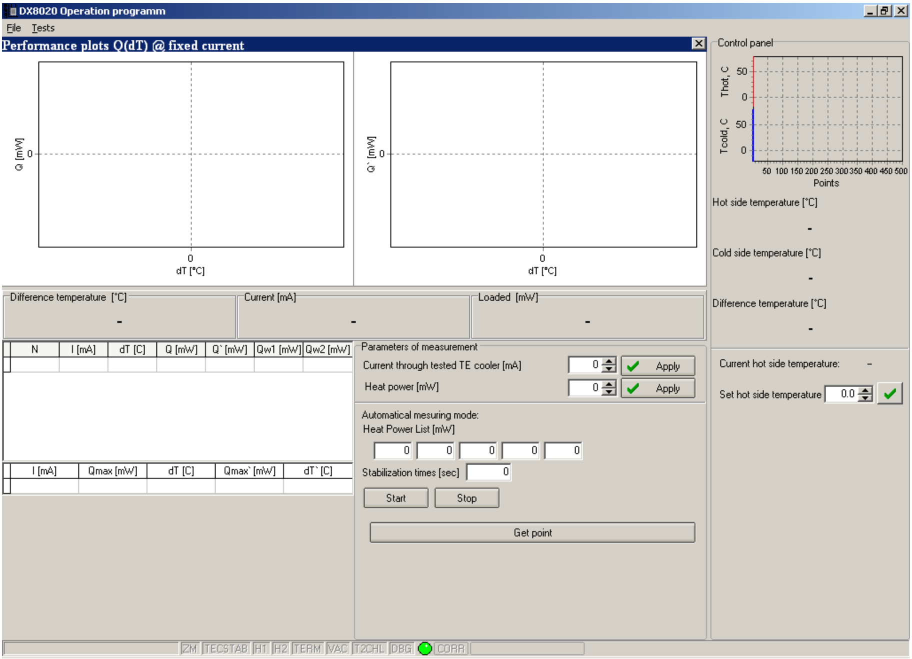
<u>Important!</u> *If you need to consider amendments to the passive heat flows through the wires before you go into this mode of measurement, specify the necessary characteristics of the wires in the box "Main Menu" - "Tests" - "Qpas Parameters", Boc-used bookmark "Standard test: $Q(dT)$".*



The wires are divided into two types:

- Type 1 - Wire of Pt resistor.
- Type 2 - wire of etalon heater.

To enter the measurements of $Q(dT)$, must choose the "Main Menu" - "Tests" - "Standard tests" - "$Q(dT)$". Window measurements looks as shown.

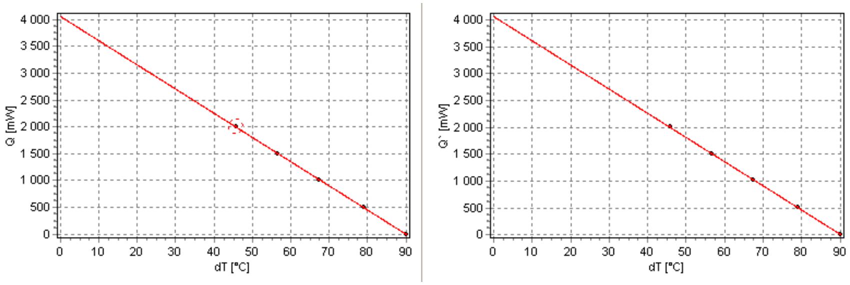


The window contains several fields:

- Fields of the plots $Q(dT)$ and $Q`(dT)$.
- Field of current values dT, I, Q.
- Table of the measured points.
- Control panel.

Field of the Plots $Q(dT)$ and $Q`(dT)$

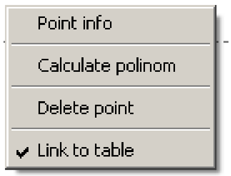
The left plot offers the results with no corrections applied; the right plot does those corrected considering passive heat flows through the wires.



If indicating a point on the plot by the mouse, the values of this point as well as the corresponding parameters are highlighted by the red color in the table.

N	I [mA]	dT [C]	Q [mW]	Q` [mW]	Qw1 [mW]	Qw2 [mW]
1	1800	90.12	0	12.566	6.936	5.630
2	1800	78.96	500	511.410	6.077	4.933

Mistaken and unnecessary points can be deleted. To do it just approach the point you want to delete by the mouse cursor until it is enclosed in the red circle. Press the right button of the mouse to obtain the context menu as shown.



To delete a point, choose "Delete point".

Field of current values dT, I, Q

This field displays current values dT, I, Q of the tested TE module.

Difference temperature [°C]	Current [mA]	Loaded [mW]
-0.2	0	1

In the manual mode with the help of these values it is possible to estimate if the module is stabilized or not.

Table of the Measured Points

This table contains the measured values as well as the value of the electric current. The bottom line summarizes the calculated values Q_{max}, dT_{max} with no corrections applied and Q'_{max}, dT'_{max} corrected by the passive heat load.

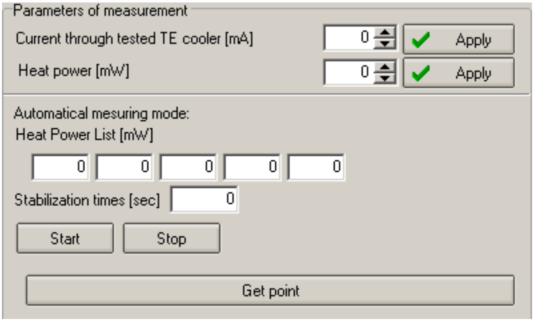
N	I [mA]	dT [C]	Q [mW]	Q` [mW]	Qw1 [mW]	Qw2 [mW]
1	1800	90.12	0	12.566	6.936	5.630
2	1800	78.96	500	511.410	6.077	4.933
3	1800	67.46	1001	1009.907	5.192	4.214
4	1800	56.59	1500	1507.991	4.356	3.535
5	1800	45.89	2000	2006.699	3.532	2.867

I [mA]	Qmax [mW]	dT [C]	Qmax` [mW]	dT` [C]
1800	4058.80	89.98	4058.80	90.26

The red-colored line corresponds to the point indicated by the mouse cursor.

Control Panel

This field allows control of the testing procedure.

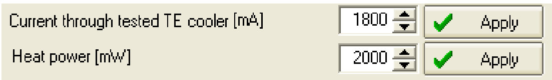


Before starting the test, it is necessary to set the temperature of the stabilizing base and wait during the time t_{stab} to achieve the stabilization.

The test can be done either manually or automatically.

Testing Manually

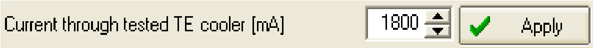
Set the electric current and heat load values and click "apply".



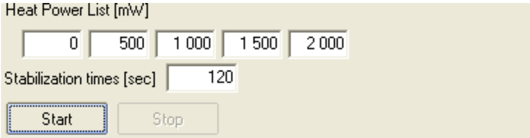
After achieving a steady-state temperature by the module cold side press the button "Get point".

Testing Automatically

Set the electric current value and click “apply".



Set the hot side stabilization time and 5 values of the heat to be pumped.



To start the measuring cycle, press the button "Start". The data will be taken automatically within the settings given.

After the test is over a linear polynomial is built by all the measured points. The values the calculated values Q_{max}, dT_{max} with no corrections applied and Q'_{max}, dT'_{max} corrected by the passive heat load are displayed.

9.3. Expert Mode

The Expert Mode objective is to measure the widened range of TE module parameters at a specified electric current with no corrections. It is possible to apply an additional measuring temperature channel and an additional heater.

In the Expert mode all the measuring telemetry can be obtained for the conditions assigned as fully as possible. The telemetry comprises the following parameters to test and control:

- Four-sensor temperature data (T_1, T_2, T_3, T_4).
- Double-channel heat loads (Q_1, Q_2).
- Tested TE module electric current.
- Tested TE module voltage.
- Thermostabilizing TE module voltage.

- The electrical resistance of thermistor (if there is one on the tested TE module).

The testing conditions are as follows:

1) A base with a heater and a thermal resistor is mounted onto the TE module cold side (see Section 7); the heater power equals the necessary value.
2) The TE module hot side is mounted onto the sample holder mounting surface (see Section 7).
3) The TE module leading wires are soldered to the connecting plates according to the TE module polarity.
4) The thermostabilizing module is switched on. The temperature $\boldsymbol{T_{hot}}$ of the thermostabilizing surface is fixed within the range available (see Table 2).
5) The facilities cover is closed.
6) The vacuum chamber is pumped out to residual pressure not exceeding $1 \cdot 10^{-2}$ mm Hg.

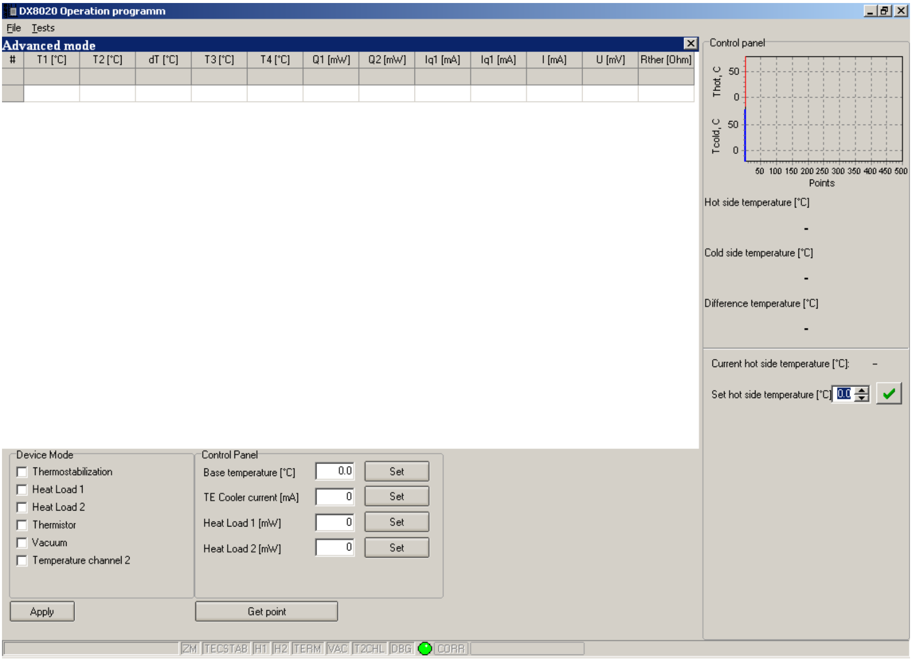
The testing procedure is as follows.

1) Set the required temperature of the thermostabilizing surface $\boldsymbol{T_{hot}}$;
2) Set the required heat load $\boldsymbol{Q_0}$ (the heater power).
3) Set the required electric current $\boldsymbol{I_0}$;
4) Wait until the thermostabilizing is steady, observing the stabilizing temperature data.
5) Measure the temperature difference $\Delta\boldsymbol{T}$ of the TE module at the given values $\boldsymbol{Q_0}$ and $\boldsymbol{I_0}$;

Important! *To calculate corrections to ΔT in the expert mode it is necessary to measure $Q(\Delta T)$ in the vicinity of the operating point (that is, to measure $Q(\Delta T)$ at a given current I in the standard mode).*

For the expert testing of a TE module, it is necessary to choose "Main Menu"-"Tests"- Expert Mode".

Window looks as shown.

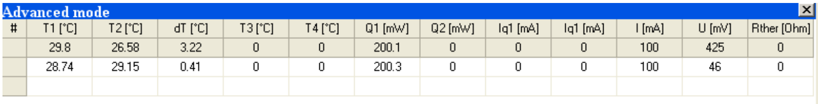


The window contains two functional fields:

- table of measured points.
- control panel.

Table of Measured Points

The table contains current values of parameters of a tested TE module (grey line) and those taken for the test results (white lines).

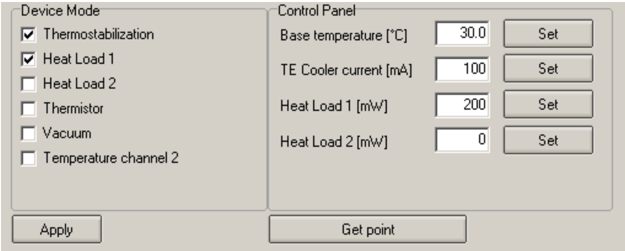


Advanced mode

#	T1 [°C]	T2 [°C]	dT [°C]	T3 [°C]	T4 [°C]	Q1 [mW]	Q2 [mW]	Iq1 [mA]	Iq1 [mA]	I [mA]	U [mV]	Rther [Ohm]
	29.8	26.58	3.22	0	0	200.1	0	0	0	100	425	0
	28.74	29.15	0.41	0	0	200.3	0	0	0	100	46	0

Control Panel

In this field you may change the device mode and set the parameters at which the TE module is to be tested.



For example, in the figure given (above), the mode is the following: the device mode is thermal stabilization of the hot side (the base), heater 1 is on; the measurement parameters: the base temperature is 30ºC, TE module electric current is 100 mA, the heater is 200 mW.

To take the measured result, press the button "Get point".

9.4. $Z - R - \tau$ -Metering

In these testing modes the following TE module parameters are measured: electrical resistance AC R; Figure-of-Merit Z; time constant τ. See Annex VIII. Measurement of Figure-of-Merit.

Like the $Z - R - \tau$ Meters developed by PL Engineering the DX8020 enable testing the following parameters of TE modules:

- AC resistance (AC R).
- Figure-of-Merit (Z).
- Time constant (τ).

The TE module Figure-of-merit Z is measured by the Harman method. Here all the limitations common for the $Z-R-\tau$ meters are to be followed (see "*Annex VIII*. *Measurement* of Figure-of-Merit"). The methods of the DX8020 are meant for measuring Z of single-stage TE modules.

Important! *The testing of the value Z for two-stage TE modules are rather estimative. For multistage TE modules the Harman method is not applicable. The quality of TE modules with more stages can be estimated by measuring the module electric resistance AC R and the time constant.*

For brevity we call $Z-R-\tau$-Meter as Z-Meter.

9.4.1. TE Module Free in the Ambient

In this testing mode the TE module to be tested is in free heat exchange with the air/vacuum environment.

The aim of this option is:

- to offer express assessments of TE module quality and necessity of its direct measurements by testing the values $Z,\ R,\ \tau$ of a TE module at room temperature T_a~ 300 K.
- ensure a correlation between measurements of $Z,\ R,\ \tau$ in vacuum and air and evaluate the accuracy of mathematical estimation of air impact on the results of measurements.

The testing conditions are as follows.

1) Both the TE module sides are free.
2) The TE module leading wires are soldered onto the connecting plates.
3) The thermostabilizing TE module is off.
4) The DX8020 cover is closed.

5) For testing in vacuum, the chamber is pumped out to residual pressure not exceeding $1 \cdot 10^{-2}$ mm Hg.

The testing procedure is as follows.

1) Measure the ambient temperature T_a .

2) Measure the TE module AC R (hereinafter this value comprises both the TE module and its wires electric resistance AC R: $R = R_{TEC} + R_{wires}$).

3) Set the overall measuring time MT.

4) Set the TE module electric current $I_{test} = 0.01 I_{max}$ (see the TE module Standard Specifications); press the button “measure". The automatic testing procedure is started.

5) The automatic testing procedure is as follows:

   5.1) The temporal dependences of the TE module total voltage $U(t)_{\pm}$ and the Seebeck voltage $U_{\alpha}(t)_{\pm}$ are measured within the time range $[0..MT]$ sequentially at the current $\pm I_{test}$; the telemetry $U_{\alpha}(t_i)_{\pm}$ is displayed.

   5.2) The curves $U_{\alpha}(t_i)_{\pm}$ are interpolated by the exponents:

$$U_{\alpha}(t_i)_{\pm} = Ust_{\alpha\pm}(1 - e^{-t/\tau_{\pm}}) \quad (9.3)$$

As a result of this interpolation the corresponding time constants $\tau_{\pm}$ and the steady-state voltage values $Ust_{\alpha\pm}$ are obtained for both polarities.

Important! *To proceed with the $Z - R - \tau$-meter measurements be sure that the period t_{test} is enough for the module to achieve the steady state, which can be controlled by the visual telemetry*

   5.3) The TE module time constant is found as the average: $\tau_{av} = 0.5(\tau_{+} + \tau_{-})$

5.4) For each polarity the ohmic voltage is found *via* averaging over the last 10 measured points:

$$U_{R\pm} = \frac{1}{10} \sum_{i \geq (N-10)} \left(U(t_i)_\pm - U_\alpha(t_i)_\pm\right) \qquad (9.4)$$

5.5) With no account of the corrections the values $Z_\pm$ are calculated as:

$$Z_\pm = \frac{1}{T_{hot}} \frac{U_{st\ \alpha\pm}}{U_{R\pm}} \qquad (9.5)$$

Then the average Z is calculated as:

$$Z_{av} = \frac{1}{2}(Z_+ + Z_-) \qquad (9.6)$$

5.6) With the help of calculated corrections, it is possible to allow for the inequality between the ambient temperature and the average temperature of the module (b_T), heat flow between the pellets (b_{th}) and thermal losses on the wires (b_r).

<u>Important!</u> The corrections are only applied to the value Z_{av}.

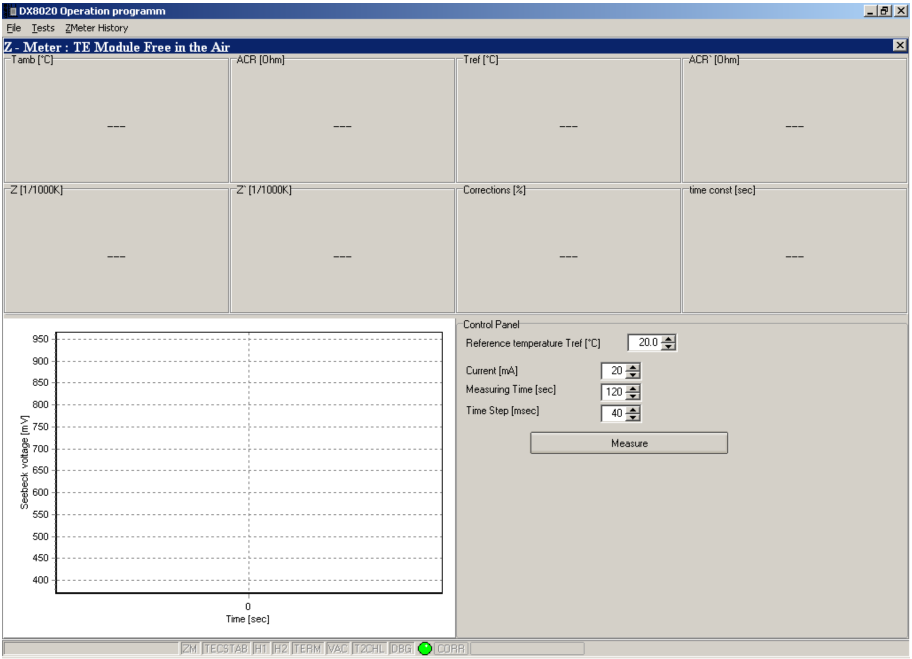
$$Z'_{av} = \frac{Z_{av}}{(1 + b_T)}(1 + b_{th})(1 + b_r) \qquad (9.7)$$

Therefore, the whole correction can be written as:

$$corr = \frac{(1 + b_{th})(1 + b_r)}{1 + b_T} \qquad (9.8)$$

All the expressions for the corrections are given in *Annex VIII. Measurement* of Figure-of-Merit. It is only the corrections values that the choice of the environment (air/vacuum) tells upon.

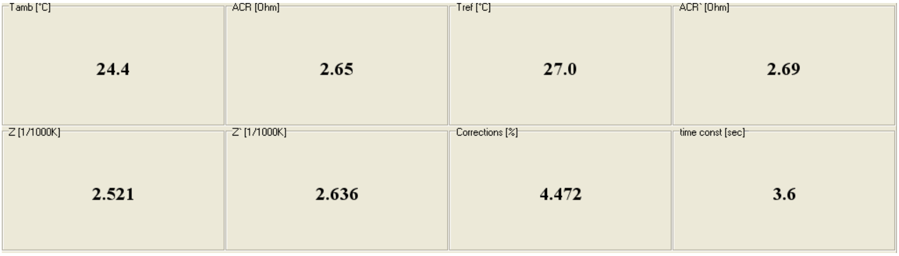
To select this testing mode, choose from the Main Menu bar the command "Main Menu"-"Tests"-"Z-meter"- "TE Module Free in the air" or "TE Module Free in vacuum". The measurement window is illustrated below.



The window consists of three fields:

- results field.
- temporal behaviour of the Seebeck voltage.
- control panel.

Results Field

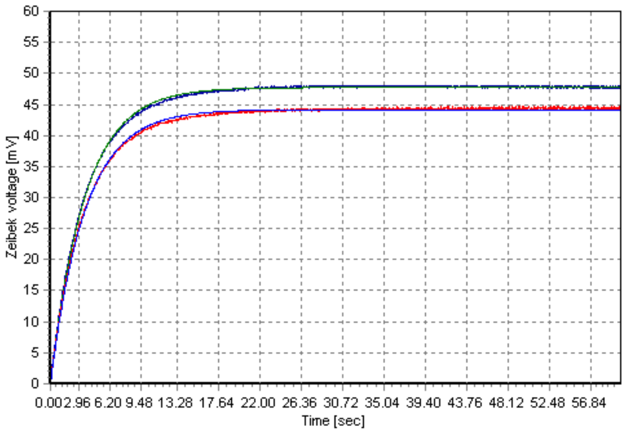


The following results are displayed:

- T_{amb} – ambient temperature.
- AC R – TE module electrical resistance (alternating current).
- AC R' – ACR referred to T_{ref},
- Z – TE module Figure-of-Merit.
- Z' – TE module Figure-of-Merit with corrections applied.
- Corrections – correction coefficient to Z.
- Time Const – TE module time constant.

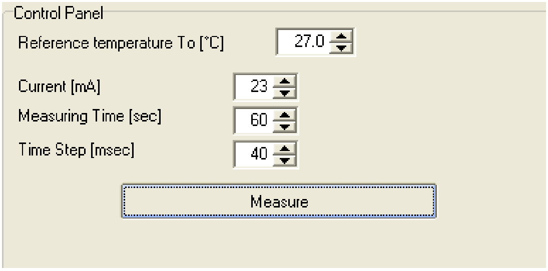
Temporal behavior of the Seebeck voltage

This curve (see figure below) displays the dynamics of the Seebeck voltage at the test current of two polarities. Each experimental curve is accompanied by the interpolation one.



Control Panel

The control panel allows setting the measurement parameters.



The following parameters are to be set:

- Reference temperature (T_{ref}) – temperature AC R is referred to.
- Current – TE module electric current ($0.01I_{max}$ is recommended).
- Measuring Time.
- Time Step (recommended to increase for longer testing).

9.4.2. TE Module with the Hot Side Temperature Stabilized

This mode is intended for $Z - R - \tau$- testing of a TE module at the given temperature. See *Annex* VIII. Measurement of Figure-of-Merit.

In this mode one side of a TE module is stabilized at a temperature T_{hot}. The measurements are performed in vacuum.

The aim of this option is to measure the parameters Z, R, τ at a given temperature, which may differ from the room temperature.

The testing conditions are as follows.

1) One side of the TE module is free, the other is mounted onto the thermostabilized surface (see Section 7).
2) The TE module leading wires are soldered onto the connecting plates.
3) The thermostabilizing TE module is on. The thermostabilizing surface temperature $\boldsymbol{T_{hot}}$ is fixed within the range available (see Table).
4) The DX8020 chamber cover is closed.
5) The chamber is pumped out to residual pressure not exceeding $1 \cdot 10^{-2}$ mm Hg.

The testing procedure is as follows:

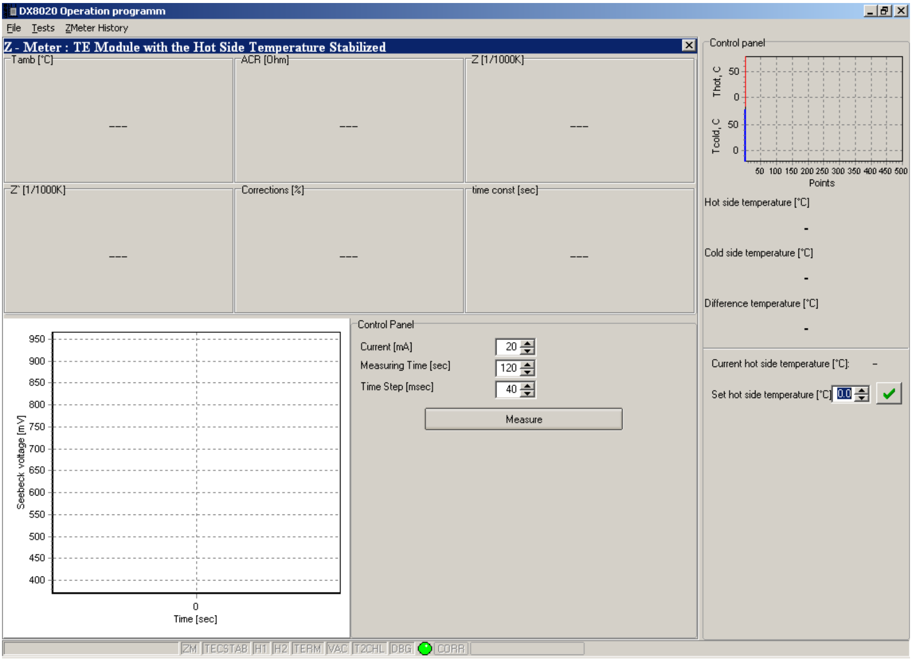
1) Set the temperature of the thermostabilizing surface $\boldsymbol{T_{hot}}$; wait until the thermostabilizing is steady.
2) The measurements 2) – 5) of Section 9.4.1. Eq. (9.5) is modified as:

$$Z\pm = \frac{1}{T_{hot}} \frac{U_{st\ \alpha\pm}}{U_{R\pm}} \tag{9.9}$$

The value Z is measured and corrected (see "*Annex VIII*. *Measurement* of Figure-of-Merit") for a TE module with $T_{hot} = const$.

The corrections only include the leading wires correction (see "*Annex IV*. *Heat* Flux along Leading Wires") and radiation (see "*Annex II.* Radiation Heat Exchange", "*Annex III.* Thermal Conductance between Pellets").

Choose the command "Main Menu" > "Tests" > "Z-meter" > "TE module with the Hot Side Temperature Stabilized".



Before testing it is necessary to set the TE module base temperature and wait until the base is stabilized (the red indicator at the bottom turns to green).

The testing procedure, parameters, functional fields, and results form are the same as in the modes " $Z - R - \tau$ -Meter for TE Module Free (air/vacuum)".

9.5. TE Materails Properties

This testing mode enables experimental estimate of TE materials properties of the tested TE module: the Seebeck coefficient α and electrical conductivity σ at temperature available.

The objective of the given option is to estimate the properties of TE materials of the TE module pellets at the given temperature T_{hot} or in a temperature range available using the measurements of the parameters Z and R, as well as the stationary Seebeck voltage value U_{α} and the corresponding value of the temperature difference ΔT.

The TE properties to be obtained are:

- Electrical conductivity.
- Seebeck coefficient.

The estimates obtained are the average values for the n- and p- type materials.

Important: *It is only one-stage TE modules with known geometrical parameters that can be tested in this option.*

The testing conditions are as follows.

1) One side of the TE module is stabilized at the temperature $\boldsymbol{T_{hot}}$.
2) The TE module leading wires are soldered onto the connecting plates.
3) The thermostabilizing TE module is on. The thermostabilizing surface temperature $\boldsymbol{T_{hot}}$ is fixed within the range available (see Table).
4) The chamber cover is closed.
5) The chamber is pumped out to residual pressure not exceeding $1 \cdot 10^{-2}$ mm Hg.

The testing procedure is as follows.

1) Set the temperature of the thermostabilizing surface $\boldsymbol{T_{hot}}$; wait until the thermostabilizing is steady.
2) Repeat the $\boldsymbol{Z-R-\tau}$-metering of the TE module with the hot side temperature $\boldsymbol{T_{hot}}$ stabilized; the values of AC $\boldsymbol{R}$ and $\boldsymbol{Z}$ of the TE module are found (with / with no corrections applied.

3) By the measured AC $\boldsymbol{R}$ at the given temperature $\boldsymbol{T_{hot}}$ the electrical conductivity $\boldsymbol{\sigma}$ [1/Ohm·m] of the TE material is estimated as:

a. $R_{pellet} = \frac{(R-2r-NR_{me})}{N}$

b. $\rho = R_{pellet}\frac{s}{l}$ (9.10)

c. $\sigma = \frac{1}{\rho}$

Here $\boldsymbol{N}$ - TE module pellets number.

The electrical resistance $\boldsymbol{R_{me}}$ is calculated as:

$$R_{me} = \rho_{Cu}\frac{d + 2/3\,w}{wl_{me}} \quad (9.11)$$

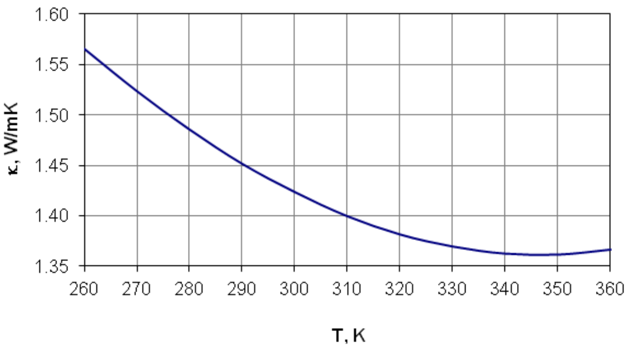
where $\boldsymbol{d}$ - distance between pellets of the TE module; $\boldsymbol{w}$ - their width; $\boldsymbol{l_{me}}$ - the metal junction's thickness.

4) By the known polynomial temperature dependence $\boldsymbol{k} = \frac{1}{2}(\boldsymbol{k_n} + \boldsymbol{k_p})$ the Seebeck coefficient is calculated by:

$$\alpha = \sqrt{\frac{Zk}{\sigma}} \quad (9.12)$$

The corrected parameter $\boldsymbol{\alpha}$ corresponds to the corrected Figure-of-Merit $\boldsymbol{Z}$.

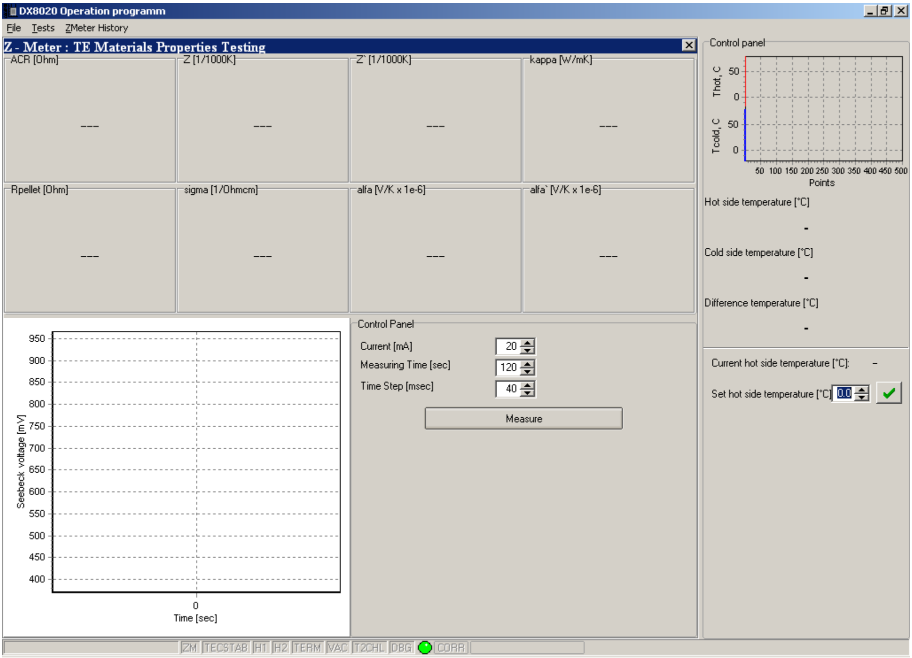
Among the three parameters $\boldsymbol{\alpha}, \boldsymbol{\sigma}, \boldsymbol{k}$ the parameter $\boldsymbol{k}$ is the least sensitive to charge carriers' properties, that is why a standard κ(T) can serve for estimating the coefficient $\boldsymbol{\alpha}$. In the figure below the dependence $\boldsymbol{k}(\boldsymbol{T})$ averaged for n- and p-type room temperature optimized TE materials is given. This curve is a default function the DX8020 software offers.



Important: *The function $k(T)$ can be changed by introducing new factors of the polynomial (see the file DX8020/Parameters.ini).*

If necessary, items 1-7 are performed for a new T_{hot}.

Choose the command "Main Menu" > "Tests" > "TE Materials Properties Testing".



The testing procedure, parameters, functional fields are like the mode "TE Module with the Hot Side Temperature Stabilized".

ANNEX I. CONVECTIONAL HEAT EXCHANGE

Coefficient of convection heat exchange per surface unit α_{conv} [W/(m^2·K)] is written as

$$\alpha_{conv} = \frac{k}{x} Nu, Nu = C(Gr\, Pr)^n \quad (I.1)$$

where Nu - the Nusselt number; Gr, Pr - Grashof and Prandtl numbers, respectively.

The Grashof number Gr is described as:

$$Gr = \frac{g\beta\Delta T x^3}{v^2} \quad (I.2)$$

where $g = 9.8\, m/c^2$, $\beta = 1/T$ [1/K] - linear expansion coefficient for the ambient gas at given conditions (usually at normal ones); T [K] - the gas absolute temperature; ΔT - temperature difference considered; x [m] - characteristic linear size of the object (we recommend it to be the bigger side of the surface involved in the heat exchange); v [m^2/s] - kinematic viscosity.

The Prandtl number Pr and gas thermal diffusivity α can be calculated as:

$$Pr = \frac{v}{\alpha} \quad (I.3)$$

$$\alpha = \frac{k}{c_p \rho} \quad (I.4)$$

where ρ [kg/m^3] - gas density; c_p [J/(kg·K)] - gas heat capacity at constant pressure.

If $1 < Pr < 1000$ and $10^3 < Gr\, Pr < 10^9$, we deal with a laminar flow and then the coefficients in Eq. (7.1) are the following $C = 0.75$, $n = 0.25$, i.e.:

$$\alpha_{conv} = \frac{k}{x} 0.75 (Gr\ Pr)^{0.25} \qquad (I.5)$$

Table I.1 offers dry air parameters at normal pressure and temperature 20 ºC and 30 ºC.

Table I.1

T, ºC	ρ, kg/m ^{3}	c_p, J /(kg • K)	κ, W/(m • K)	$\nu \cdot 10^6$, m^2/s
20	1.205	1000	0.0260	15.06
30	1.165	1000	0.0268	16.00

Consider an example of calculations. For $\Delta T = 3K$ (approximately true in Z-metering). In Table I.2 the estimates for α_{conv} are given for some TE modules in the air at 20 ºC.

Table I.2

TE module type	$x \cdot 10^3$, m	α_{conv}, W/m^{2}K (20ºC)
1MC04-004-xx	3.2	10.87
1MC06-018-xx	6.0	9.29
1MC04-070-xx	9.6	8.26
1MC06-105-xx	15.0	7.38

The full passive convectional flow onto the surface F_1 (the TE module substrate, including lateral sides) is:

$$Q_{pas\ conv} = \alpha_{conv} F_1 \Delta T \qquad (I.6)$$

ANNEX II. RADIATION HEAT EXCHANGE

Designations:

"1" - object (TE module):

Surface – F_1, m^2 (TE module surface);

A_1 – emissivity;

T_1 – temperature.

"2" - hemisphere cover:

Surface – F_2, m^2;

A_2 – emissivity;

T_2 – temperature.

General data:

The hemisphere cover surface, m^2: $F_2 = 2\pi R_{cover}^2 = 0.062\, m^2$ ($R_{cover} = 10\ cm$).

Emissivities:

$\boldsymbol{A_1 = 0.8}$ (typical for ceramics),

$\boldsymbol{A_2 = 0.45}$ (typical for stainless steel).

The method of estimating effective emissivity between bodies 1 and 2 can be obtained as:

$$A_{12} = \frac{1}{\frac{1}{A_1} + \frac{F_1}{F_2}\left(\frac{1}{A_2} - 1\right)} \qquad \text{(II.1)}$$

For micro modules $\boldsymbol{F_2 \ll F_1}$ and effective emissivity nearly coincides with the value $\boldsymbol{A_1}$. Further we consider this case.

In the Standard option the radiation heat exchange coefficient α_{rad} [W/m^{2}K] can be estimated as:

$$\alpha_{rad} = \sigma_{SB} A_1 (T_{hot}^2 + T_{cold}^2)(T_{hot} + T_{cold}) \qquad \text{(II.2)}$$

where $\boldsymbol{\sigma_{SB}}$ *- Stefan-Boltzmann constant.*

For testing a TE module in the $\boldsymbol{Z - R - \tau}$ -metering option, free heat exchange mode the value $\boldsymbol{\alpha_{rad}}$ equals the following:

$$\alpha_{rad} = 4\sigma_{SB} A_1 T_a^3 \qquad \text{(II.3)}$$

For testing a TE module in the $\boldsymbol{Z - R - \tau}$-metering option and the base side temperature stabilized at $\boldsymbol{T_{hot}}$, the value $\boldsymbol{\alpha_{rad}}$ - defined via $\boldsymbol{T_{hot}}$:

$$\alpha_{rad} = 4\sigma_{SB} A_1 T_{hot}^3 \qquad \text{(II.4)}$$

Then the full passive radiation flow onto the surface F_1 (the TE module substrate, including lateral sides) is:

$$Q_{pas\ conv} = \alpha_{rad} F_1 \Delta T \qquad \text{(II.5)}$$

ANNEX III. THERMAL CONDUCTANCE BETWEEN PELLETS

Consider one stage of a TE module. The correction b_{th} characterizes additional thermal conductivity between the pellets:

$$k' = k(1 + b_{th}) \qquad \text{(III.1)}$$

where k - p-n type average thermal conductivity of TE material.

The value b_{th} is estimated as the sum of corrections for thermal conductivity in the air and radiation:

$$b_{th} = B_{air} + B_{rad} \qquad \text{(III.2)}$$

where B_{air} - correction for thermal conductivity in the air; B_{rad} - that for radiation.

Introduce β as the pellets filling coefficient:

$$\beta = \frac{ns}{S} \qquad \text{(III.3)}$$

where n - pellets number; s - pellet cross-section; S - cold substrate surface.

The value B_{air} is calculated as:

$$B_{air} = \frac{k_{air}}{k}\left(\frac{1}{\beta} - 1\right) \qquad \text{(III.4)}$$

The correction for radiation can be written as:

$$B_{rad} = \frac{l}{k}\gamma\sigma_{SB}\left(\frac{1}{\beta} - 1\right)(T_{hot} + T_{cold})(T_{hot}^2 + T_{cold}^2) \qquad \text{(III.5)}$$

where $\boldsymbol{\sigma_{SB}}$ *- the Stefan-Boltzmann constant;* $\boldsymbol{\gamma}$ *- emissivity of the inner side of the TE module substrate;* $\boldsymbol{T_{hot}}$ *- the hot side temperature;* $\boldsymbol{T_{cold}}$ *- the cold side temperature.*

For small electric currents (for example while measuring $\boldsymbol{Z}$) $\boldsymbol{T_{hot}} \approx \boldsymbol{T_{cold}} \approx \boldsymbol{T_a}$, and formula (9.5) can be rewritten as:

$$B_{rad} = \frac{4l}{k}\gamma\sigma_{SB}\left(\frac{1}{\beta} - 1\right)T_a^3 \qquad \text{(III.6)}$$

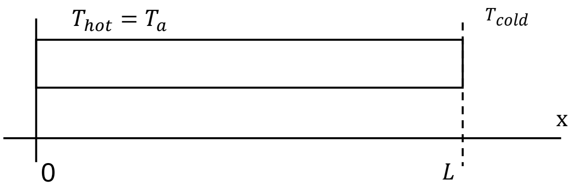
In Table III.1 we give the calculated results for $\boldsymbol{B_{air}}$ and $\boldsymbol{B_{rad}}$ for typical TE modules at $\boldsymbol{T_a = 293}$ К for typical temperature of $\boldsymbol{Z, R, \tau}$-metering: $\boldsymbol{T_{hot} = 293}$ К, $\boldsymbol{T_{cold} = 290}$ К ($\Delta\boldsymbol{T = 3\ K}$).

Table III.1

TE module type	β	B_{air}	B_{rad}
1MC04-004-05	0.25	0.055	0.005
1MC04-004-15	0.25	0.055	0.014
1MC06-018-05	0.36	0.032	0.003
1MC06-018-15	0.36	0.032	0.009

ANNEX IV. HEAT FLUX ALONG LEADING WIRES

Consider a wire with no insulation, the cross-section is $\boldsymbol{S}$, the length is $\boldsymbol{L}$, the cross-section perimeter is $\boldsymbol{U}$. Let $\boldsymbol{\alpha}$ stand for the heat exchange coefficient per the wire surface unit.



If $x = 0$ marks the hot end of the wire, the cold end has the coordinate $x = L$. The heat conduction equation for such a pellet exposed to the electric current of the density j has the following form in one-dimensional equation:

$$k\frac{d^2T(x)}{dx^2} + j^2\rho + A\big(T_a - T(x)\big) = 0 \qquad \text{(IV.1)}$$

where k - the wire material thermal conductivity; ρ - its electrical resistivity; $T(x)$ - temperature in the coordinate x.

The value A is defined as:

$$A = \alpha\frac{U}{S} \qquad \text{(IV.2)}$$

We take the following boundary conditions: the cold end temperature is T_{cold}, the hot end temperature is T_{hot}:

$$T(x)_{x=0} = T_{hot}, T(x)_{x=L} = T_{cold} \qquad \text{(IV.3)}$$

The heat flux arriving at the cold end equals

$$Q = -kS\frac{dT}{dx}\bigg|_{x=L} \qquad \text{(IV.4)}$$

Solving Eq. (10.1) we find the temperature distribution along the wire:

$$T(x) = T_a - \frac{j^2\rho}{A}(e^{px} - 1) + \left\{\frac{j^2\rho}{A}(e^{px} - 1) - \Delta T\right\}\frac{sh(pL)}{sh(pL)} \qquad \text{(IV.5)}$$

where

$$p = \sqrt{\frac{A}{k}}, \Delta T = T_{hot} - T_{cold}$$

The passive heat flow onto the cold end is yielded (10.4) and (10.5):

$$Q_{pas} = NS\sqrt{Ak}\left[\frac{j^2\rho}{A}e^{pL} + \left\{\frac{j^2\rho}{A}(1 - e^{pL}) + \Delta T\right\}\frac{ch(pL)}{sh(pL)}\right] \qquad \text{(IV.6)}$$

In vacuum the radiation heat exchange coefficient [W/(m^2·K)] can be estimated as:

$$\sigma_{rad} = \gamma\sigma_{SB}(T_{av} + T_a)(T_{av}^2 + T_a^2) \qquad \text{(IV.7)}$$

where $T_{av} = \frac{1}{2}(T_{hot} + T_{cold})$, σ_{SB} *- the Stefan-Boltzmann constant,* γ *is the emissivity of the wire surface.* T_a *is the ambient temperature, or the temperature of the cover, it is taken 20ºC=293 K by default.*

In the TEC Expert DX8020 methods the corrections on the passive heat flow along the wires are considered for the TE module cold side only (no corrections for intermediate substrates). There may be two different types of these wires:

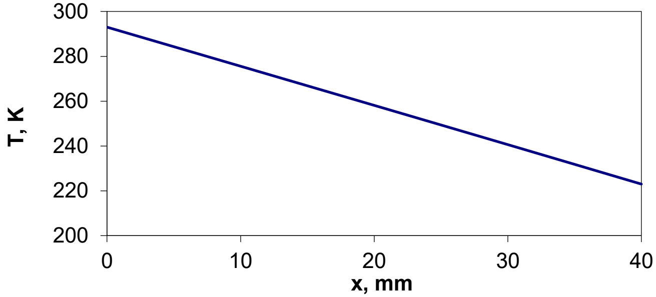
1) Thermistor wires (Pt);

2) Heater wires.

Consider exemplary calculations for both the types.

1) The common parameters of thermistor wires: the material is copper, $k = 400\,W/mK$, $\rho = 1.667 \cdot 10^{-8}\,Ohm \cdot m$. The wire diameter is 0.07 mm, the length is $L = 40\,mm$. The electric current is 1 mA (approximately for the 100 Ohm thermoresistor). The ambient temperature $T_a = 20℃$. The hot end temperature $T_{hot} = T_a$. The cold end temperature $T_{cold} = -50℃$ (approximate minimal temperature of a single-stage TE module cold substrate at I_{max} and $T_a = 20℃$). The heat exchange for the wire surface is that of radiation. For copper we take the value of emissivity $\gamma = 0.02$ (polished copper).

   Then the heat exchange coefficient α equals $\alpha = 0.095\,W/(m^2K)$. At the small current (here $\frac{j^2\rho}{A} \ll \Delta T, \frac{j^2\rho}{A} \sim 0.173$) and if the wire thermal conductance is high enough while the radiation heat exchange from the surface is low: $pL \ll 1$ (here the value pL is equal to 0.16), the temperature distribution along the wire is nearly linear – in figure below you are given the results of the exact calculation:



   I.e. Eq. (IV.5) can be rewritten as:

$$T(x) = T_a - \Delta T \frac{sh(px)}{sh(pL)} \qquad \text{(IV.8)}$$

and the expression for the heat flow at the cold end of the wire:

$$Q_{pas} = k\frac{S}{L}\Delta T \quad \text{(IV.9)}$$

The exact calculation resulted from Eqs. (IV.5), (IV.6): $Q = 7.189\ mW$. The result of the approximate calculation yields: $Q = 7.180\ mW$. We see the results are very close.

In the software Eq. (IV.9). is applied for thermistor. For N wires Eq. (IV.9). is written as:

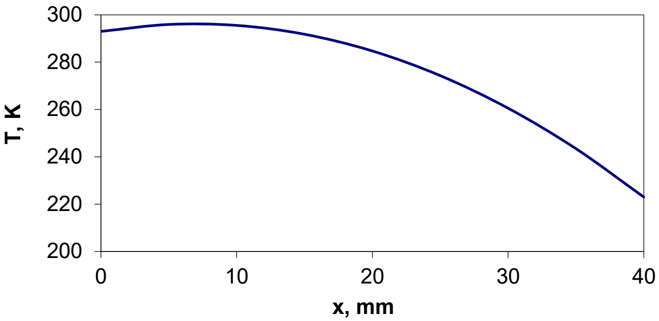
$$Q_{pas} = Nk\frac{S}{L}\Delta T \quad \text{(IV.10)}$$

For $N = 2$ the thermoresistor wires with the parameters and at the conditions given provide the summed passive heat load onto the cold substrate 5.39 mW.

2) Consider the following parameters of the heater wires: the material is copper, $k = 400\ W/mK$, $\rho = 1.667 \cdot 10^{-8} Ohm \cdot m$. The wire diameter is 0.15 mm, the length is $L = 40\ mm$. The electric current is 1 A (approximately for the heater of the nominal 6.8 Ohm at the load 6.8 W). The ambient temperature $T_a = 20℃$. For an estimation of the passive heat load in the standard $Q(\Delta T)$ measuring option we take $T_{cold} = -20\ ℃$.

The heat exchange for the wire surface is that of radiation. For copper we take the value of emissivity $\gamma = 0.02$ (polished copper). Then the heat exchange coefficient equals $\alpha = 0.095\ W/(m2 \cdot K)$.

For this instance, the temperature distribution along the wire is non-linear.



In the calculations the exact formulae (IV.5-IV.6) are necessary. As a result, we have $Q_{pas} = 31\,mW$. The approximate Eq. (10.9), considering thermal conductance only would have been: $Q_{pas} = 12\,mW$, which is too rough an underestimation.

In the software for the heater correction Eq. (IV.6) is applied. For N wires Eq. (IV.6) is written as follows:

$$Q_{pas} = NS\sqrt{Ak}\left[\frac{j^2\rho}{A}e^{pL} + \left\{\frac{j^2\rho}{A}(1 - e^{pL}) + \Delta T\right\}\frac{ch(pL)}{sh(pL)}\right] \quad \text{(IV.11)}$$

For $N = 2$ the heater wires with the parameters and at the conditions given provide the summed passive heat load onto the cold substrate 62 mW.

ANNEX V. N-POWER POLYNOMIAL INTERPOLATION

The polynomial interpolation approach suggested is based on the least squares method.

Let us take a two-dimensional set of N points $y_i(x_i)$. Consider an n-power polynomial:

$$y(x) = A_0 + A_1 x + A_2 x^2 + \ldots + A_{n-1}x^{n-1} + A_n x^n = \sum_{j=0}^{N} A_j \quad \text{(V.1)}$$

Introducing the following coefficients:

$$a_{2n} = \sum_{i=1}^{N} x_i^{2n}, a_{2n-1} = \sum_{i=1}^{N} x_i^{2n-1}, \ldots, a_2 = \sum_{i=1}^{N} x_i^2$$

$$a_1 = \sum_{i=1}^{N} x_i, a_0 = N;$$

$$b_n = \sum_{i=1}^{N} y_i x_i^n, b_{n-1} = \sum_{i=1}^{N} y_i x_i^{n-1}, \ldots, b_1 = \sum_{i=1}^{N} x_i y_i \quad \text{(V.2)}$$

$$b_0 = \sum_{i=1}^{N} y_i$$

We solve the system of $(n + 1)$ equations and find the coefficient A_j:

$$A_n \cdot a_{2n} + A_{n-1} \cdot a_{2n-1} + \ldots + A_1 \cdot a_{2n-n} + A_0 \cdot a_{n-1} - b_n = 0$$

$$A_n \cdot a_{2n-1} + A_{n-1} \cdot a_{2n-2} + \ldots + A_1 \cdot a_{2n-1} + A_0 \cdot a_{n-2} - b_{n-1} = 0 \quad \text{(V.3)}$$

$$\ldots$$

$$A_n \cdot a_{n+1} + A_{n-1} \cdot a_n + \ldots + A_1 \cdot a_2 + A_0 \cdot a_1 - b_1 = 0$$

$$A_n \cdot a_n + A_{n-1} \cdot a_{n-1} + \ \ldots + A_1 \cdot a_1 + A_0 \cdot a_0 - b_0 = 0$$

The mean square deviation σ is given by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(P(x_i) - y_i)^2}{N}} \qquad \text{(V.4)}$$

Let us consider an example of 2-power polynomial:

$$y(x) = Ax^2 + Bx + C \qquad \text{(V.5)}$$

If the following designations are true:

$$a = \sum_{i=1}^{N} x_i^4, b = \sum_{i=1}^{N} x_i^3, \ c = \sum_{i=1}^{N} x_i^2, \ d = \sum_{i=1}^{N} x_i,$$

$$f = N \qquad \text{(V.6)}$$

$$aa = \sum_{i=1}^{N} y_i x_i^2, ab = \sum_{i=1}^{N} y_i x_i, ac = \sum_{i=1}^{N} y_i$$

We solve the following set of equations and find A, B, C:

$$\begin{aligned} A \cdot a + B \cdot b + C \cdot c - aa &= 0 \\ A \cdot b + B \cdot c + C \cdot d - ab &= 0 \\ A \cdot c + B \cdot d + C \cdot N - ac &= 0 \end{aligned} \qquad \text{(V.7)}$$

For the linear interpolation:

$$y(x) = Ax + B \qquad \text{(V.8)}$$

If we designate:

$$a = \sum_{i=1}^{N} x_i^2\,, \qquad b = \sum_{i=1}^{N} x_i$$
$$aa = \sum_{i=1}^{N} y_i x_i\,, \qquad ab = \sum_{i=1}^{N} y_i \tag{V.9}$$

We solve the following set of equations and find the coefficients A, B:

$$Aa + Bb - aa = 0$$
$$Ab + Bc - ab = 0 \tag{V.10}$$

ANNEX VI. MEASUREMENT OF I_{max}, ΔT_{max}

To obtain the values I_{max}, ΔT_{max} we interpolate the part of the dependence $I(\Delta T)$ in the vicinity of its maximum by a square-law polynomial (see "*Annex V*. *n-Power* Polynomial Interpolation"):

$$\Delta T(I) = AI^2 + BI + C \qquad \text{(VI.1)}$$

The interpolation is taken at the electric current segment [I_0, I_{lim}]. By default, $I_0 = 0.5I_{max}$ is the starting measured point, $I_{lim} = 1.2I_{max}$ is that finishing (I_{max} is the value taken from specifications or estimations).

Once the interpolation is over, the maximal I_{max}, ΔT_{max} are obtained as:

$$I_{max} = -\frac{B}{2A}, \qquad \Delta T_{max} = \Delta T(I_{max}) \qquad \text{(VI.2)}$$

Let us take an example. Suppose the following data are measured (see Figure VI.1). The interpolating limits are taken as $I_{lim} = 4.5\ A$, $I_0 = 1.5\ A$. The interpolation polynomial is given in Eq. (VI.3) and is illustrated in figure below.

$$\Delta T(I) = -3.913\Delta T^2 + 24.417\Delta T + 32.554 \qquad \text{(VI.3)}$$

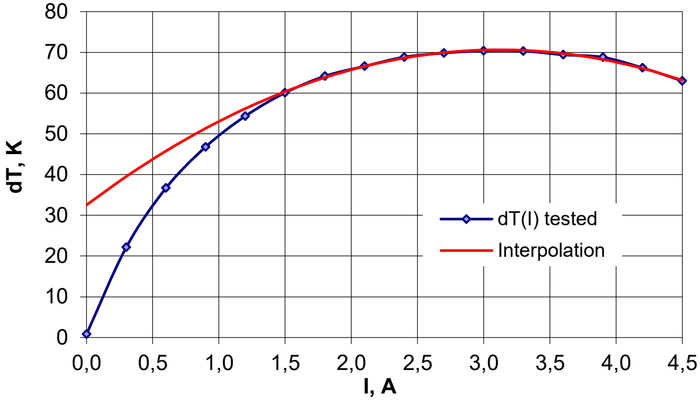


Fig. VI.1

The mean square deviation on the interval [1.5A, 4.5A]: $\sigma = 0.22$ K.

The values are $I_{max} = 3.12A$, $\Delta T_{max} = 70.642$ K.

ANNEX VII. Q_{max} MEASUREMENT.ΔT_{max} CORRECTION

The measured points are linearly interpolated and the curve $Q(\Delta T)$ is obtained (see "*Annex V*. *n-Power* Polynomial Interpolation"):

$$Q(\Delta T) = A \times \Delta T + B \quad \text{(VII.1)}$$

The value Q_{max} is defined as $Q(0) = B$:

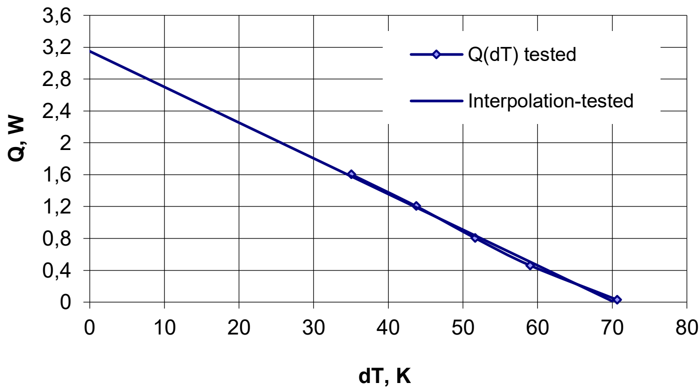
$$Q_{max} = B \quad \text{(VII.2)}$$

The value ΔT_{max} for the current I is obtained from Eq. (VII.1) при $Q = 0$:

$$\Delta T_{max} = -\frac{B}{A} \quad \text{(VII.3)}$$

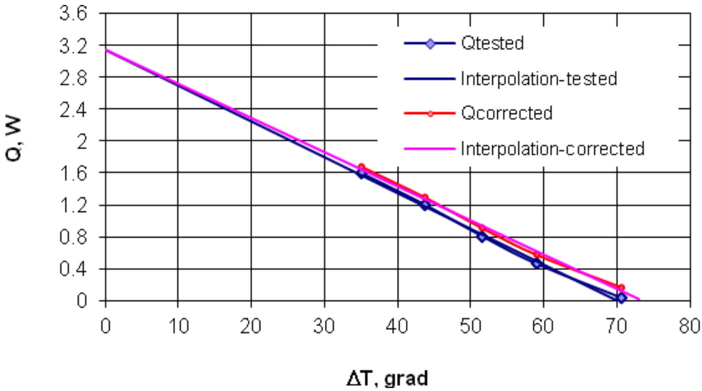
Consider an example. Suppose the measured data are given below. The calculated for the TEC $Q_{max} = 3.26\,W$, so we choose $Q_{lim} = 1.6\,W$.

The measured and interpolated results without corrections are given in figure below.



The mean square deviation in the range [35.9K, 68.7K]: $\sigma = 0.025\,W$. Eq. (VII.2) yields $Q_{max} = 2.929\,W$. With the help of Eq. (VII.3) we obtain $\Delta T_{max} = 71.35K$.

If it is necessary to calculate corrections considering a passive heat flow Q_{pas} through the wires, for each point ΔT_i the passive heat load is estimated (see "*Annex IV. Heat Flux along Leading Wires*"). By the points obtained we get a new dependence $Q' = Q + Q_{pas}$ of ΔT. After interpolating the new dependence according to the above algorithm, we find the corrected values Q'_{max}, $\Delta T'_{max}$ (see the "Standard Mode").



The corrected value $\Delta T'_{max}$ is 73.2 K.

ANNEX VIII. MEASUREMENT OF FIGURE-OF-MERIT Z

The rate equations of the heat balance for a single-stage TE module can be written as:

$$\alpha I T_{cold} - \frac{1}{2} I^2 R - k'(T_{hot} - T_{cold}) = \frac{\alpha_{cold}}{N}(T_a - T_{cold})$$
$$\alpha I T_{hot} + \frac{1}{2} I^2 R - k'(T_{hot} - T_{cold}) = \frac{\alpha_{hot}}{N}(T_{hot} - T_a) \quad \text{(VIII.1)}$$

where I - TE module current; R - electrical resistance ($R = \frac{L}{\sigma s}$, where σ - pellet material electrical conductivity; L - pellet length; s - its cross-section); T_{cold} - TE module cold side temperature; T_{hot} - TE module hot side temperature; T_a - the ambient temperature; N - pellets number; α_{cold} - summed coefficient of the heat exchange of the cold side; α_{hot} - summed coefficient of the heat exchange of the hot side. The value k' - TE module pellet effective thermal conductance considering heat flows between the pellets (see Annex III).

Eqs. (VIII.1) are solved without allowing for TE properties temperature dependence, which can be accepted as the tested currents are very small ($I \sim 0.01 I_{max}$).

We suppose that

$$\frac{\alpha_{cold}}{N} \ll k', \qquad \frac{\alpha_{hot}}{N} \ll k', \qquad I \ll \frac{k'}{\alpha} \quad \text{(VIII.2)}$$

Accurate within the first order of smallness of the values (14.2), we find the following expression $Z = \alpha^2 \sigma / k$:

$$Z = \frac{1}{T_a} \left[\frac{U_\alpha}{U_R}\right]_{av} \frac{(1 + b_{th})(1 + b_r)}{(1 + b_T)} \quad \text{(VIII.3)}$$

The ratio $\left[\frac{U_\alpha}{U_R}\right]_{av}$ in Eq. (VIII.3) must be averaged for two current directions to eliminate the terms depending on the current linearly and to extract the corrections b_{th}, b_r, b_T.

The expressions for b_{th}, b_r, b_T are as follows:

1. b_{th} is the correction for additional thermal transfer between the pellets:

$$b_{th} = B_{cond} + B_{rad}, \tag{VIII.4}$$

where the values B_{cond} and B_{rad} are calculated as shown in Annex III.

2. b_r is the correction for electrical resistance of the leading wires:

$$b_r = \frac{2r}{R_{TEC}} \tag{VIII.5}$$

where r - electrical resistance of one wire, R_{TEC} - that of the TE module without the wires: $R_{TEC} = R - 2r$.

3 b_T is the correction allowing for non-equality of the average temperature T_{av} of the module and T_a:

$$b_T = b_{T0} + b_{T1}(1 + b_{T0}) + b_{T2},$$
$$b_{T0} = \frac{I^2RN}{(\alpha_{cold} + \alpha_{hot})T_a}$$
$$b_{T1} = -\frac{\alpha_{cold}\alpha_{hot}}{(\alpha_{cold} + \alpha_{hot})kN} + \frac{(\alpha I)^2N}{(\alpha_{cold} + \alpha_{hot})k} \tag{VIII.6}$$
$$b_{T2} = \left(\frac{(\alpha_{cold} - \alpha_{hot})}{(\alpha_{cold} + \alpha_{hot})}\right)^2 \frac{I^2R}{2kT_a}$$

The values a_{cold}, a_{hot} can be estimated considering natural convection in the air (if not in vacuum) and radiation: $\alpha_{cold/hot} = (\alpha_{conv} +$

$\alpha_{rad}) S_{cold/hot}$, where α_{conv} and α_{rad} - convection and radiation heat exchange coefficients, respectively (see *Annex I and II*).

It is of vital concern that Eq. (14.3) remains true if the inequalities (14.2) are modified the following way:

$$\frac{\alpha_{cold}}{N} \ll k', \qquad \alpha_{cold} \ll \alpha_{hot}, \qquad I \ll \frac{k'}{\alpha} \tag{VIII.7}$$

It means that the method allows testing Z of a TE module if its hot side I in a rather intensive heat exchange. That is why the $Z - R - \tau$-metering option can be used for testing a TE module mounted on some header. Then $\frac{1}{\alpha_{hot}} = R_t$ is the header thermal resistance.

In the extreme case $A_{hot} = \infty$ we come to the expression for Z of a TE module, its hot side stabilized at the temperature T_{hot}:

$$Z = \frac{1}{T_{hot}} \left[\frac{U_\alpha}{U_R}\right]_{av} \frac{(1 + b_{th})(1 + b_r)}{1 - \frac{\alpha_{cold}}{kN} + \frac{I^2 R}{2kT_{hot}}} \tag{VIII.8}$$

The measured Z of a single-stage TE module allows estimating the module ΔT_{max} at the given $T_{a(hot)}$:

$$\Delta T_{max}\left(T_{a(hot)}\right) = T_{a(hot)} - \frac{\sqrt{1 + 2ZT_{a(hot)}} - 1}{Z} \tag{VIII.9}$$

REFERENCE 1. MATERIALS USEFUL PROPERTIES

Table R1

Material	Density, kg/m^3	Thermal conductivity, W/mK	Specific heat, J/kgK	Electrical resistivity, 10^{-8} mOhm
Aluminum	2 700	237	900	2.8
Copper	8 960	400	385	1.7
Gold	19 320	317	128	2.3
Iron	7 210	83	460	8.71
Lead	11 210	35	130	19.3
Molybdenum	10 220	138	249	5.6
Nickel	8 910	90	448	6.1
Platinum	21 450	72	133	10.9
Silver	10 500	429	235	1.7
Stainless steel	8 010	14.5	460	8.4
Tin	7 310	64	226	10.1
Wolfram	19 350	174	132	5.6
Zinc	7 150	112	381	5.5

REFERENCE 2. TERMS AND DEFINITIONS

Table R2

Term	Definition	Symbol	Units
Ambient temperature	Temperature of ambient where the TEC module is installed	T_a	K
Cold side temperature	Temperature of a TE module external cold substrate surface	T_{cold}	K
Hot side temperature	Temperature of a TE module (TE module system) hot (heat reject-ing) surface	T_{hot}	K
Temperature difference	The difference of the values T_{hot} and T_{cold} for a TE module (TE module system)	ΔT	K
Cooling capacity	A heat amount possible to be pumped from a TE module cold side per a time unit.	Q	W
Heat load	A heat amount supposed to be pumped by a TE module per a time unit. It should equal the value Q.	Q_l	W
Active heat load	A heat load to be pumped directly from the object to be cooled	Q_a	W
Passive heat load	A heat load that arises from the heat interchange with the ambi-ent, thermal radiation and conduc-tion accompanying processes	Q_{pas}	W
TE module electric current	Electric current flows through a TE module	I	A
TE module electric voltage	Voltage drop at TE module	U	V
TE module electric power	Electric power consumed by a TE module	P	W
Heat to be rejected	A heat amount to be transferred from the hot side of a TE module (TE module system)	Q_{hot}	W

Term	Definition	Symbol	Units
TE module electric resistance	AC resistance at a specified temperature T_a	R	Ohm
Maximum temperature difference	Maximal achievable TE module (TE module system) temperature difference at the zero TE module heat load $Q = 0$.	ΔT_{max}	K
Maximum electric current	Current at which ΔT_{max} is achieved.	I_{max}	A
Maximum cooling capacity	Maximal possible TE module cooling capacity at the zero TE module (TE module system) temperature difference $\Delta T = 0$ and $I = I_{max}$.	Q_{max}	W
Maximum voltage	TE module voltage at $\Delta T = \Delta T_{max}$ and $I = I_{max}$.	U_{max}	V
Figure-of-Merit	The combination of TE material parameters: the Seebeck coefficient α, electrical conductivity σ and thermal conductivity k as $Z = \frac{\alpha^2\sigma}{k}$. Characterizes the material efficiency at the temperature given.	Z	1/K
TE module time constant	The time necessary for the raise of the TE module temperature difference from 0 up to 0.63 of steady-state value at the given current switch on	τ	sec
TE module height		H	mm
TE module cold surface		AxB, S_{cold}	mm^2
TE module hot surface		CxD, S_{hot}	mm^2
Header	A design interface between the TE module hot side and heat sink providing a housing for the module and pin-out.		

Term	Definition	Symbol	Units
Header thermal resistance	The value characterizing temperature gradient on a header and equals this gradient divided by Q_{hot}.	R_t	K/W

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