TEC EXPERT DX8020

USER GUIDE

Moscow 2010

Version 1.20

CONTENTS

1. FOREWORD

The given 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 combines direct measurement and Z-R-τ Meter capabilities and are meant for measuring parameters of thermoelectric (TE) single-stage modules (direct measurements and Z-R-τ Meter) and multistage TE modules (direct measurements).

The equipment DX8020 enables the measurement of the following parameters – see Table 1.1.

Table 1.1

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

The DX8020 provides automatic capability to measure full specifications of a TE module at one measuring cycle in given ambient conditions.

The equipment DX80200 is intended for acceptance, qualification and research testing of TE modules.

2. DX8020 DESCRIPTION

2.1. Objectives and Technical Data

2.1.1. Objectives

The ranges of the parameters of single- and multistage TE modules measured by DX8020 are given in Table 2.1.

Table 2.1

Measured parameter	Designation	Units	Range	Accuracy
Measured 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…7	±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	1/K	0…4	
Time constant	τ	s	0…10	
Average Seebeck coefficient of TE material in the TE module	α	μV/K	100…300	
Average electric conductivity of TE material in the TE module	σ	1/Ohm·cm	400…2500	

2.1.2. Technical Data

2.1.2.1 Technical data of the facilities DX8020 are given in Table 2.2.

Table 2.2

Parameter	Designation	Units	Range	Accuracy
Tested TE module substrate max dimensions	CxD	mm²	30x30	
Tested TE module max height	H	mm	30	
Tested TE module electric current	Q	A	0…6	0.005
Tested TE module heat load	Q_{add}	W	0…0.5	0.005
Additional heat load on a stage of a multistage TE module	T_{hot}	W	-10…85	0.2
Thermostabilizing surface temperature	Q_{hot}	ºC	0…40	
Maximum heat rejection	ΔI	W	0.001	
Minimum electric current modification step	ΔT_{hot}	A	1	0.2
Minimum thermostabilizing temperature modification step	Stabilization time		From 10 s to 30 min	
Time of temperature stabilizing	Trace gases pressure		Not exceeding $1x10^{-2}$ mm Hg	

2.1.2.2 Electric power consumption:

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

2.1.2.3 The equipment DX8020 is meant for laboratory measurements at the ambient temperature 25±3ºC and relative humidity up to 80%..

2.2. Standard Kit

The equipment comprises the following:

- vacuum table;
- sample holder;
- control block;
- pumping system Mini-TASK;
- software;
- interface cables set.

2.3. DX8020 Arrangement

1) The testing part of the device is a vacuum table (see Figure 2.3-1) with the base thermally stabilized. There is a sample holder on it. A TE module to be tested is mounted on the sample holder.

2) The sample holder temperature is stabilized by the TE module TM-127-1.4-6.0, its consumption controlled.

3) The heat from the hot side of the thermostabilizing TE module is rejected by the electric fan CNPS7000A-Cu.

4) The leading wires of thermal resistors and the wires of the heaters are soldered to the mounting pads of the printed circuit board of the sample holder according to the diagram given in Figure 2.3-2.

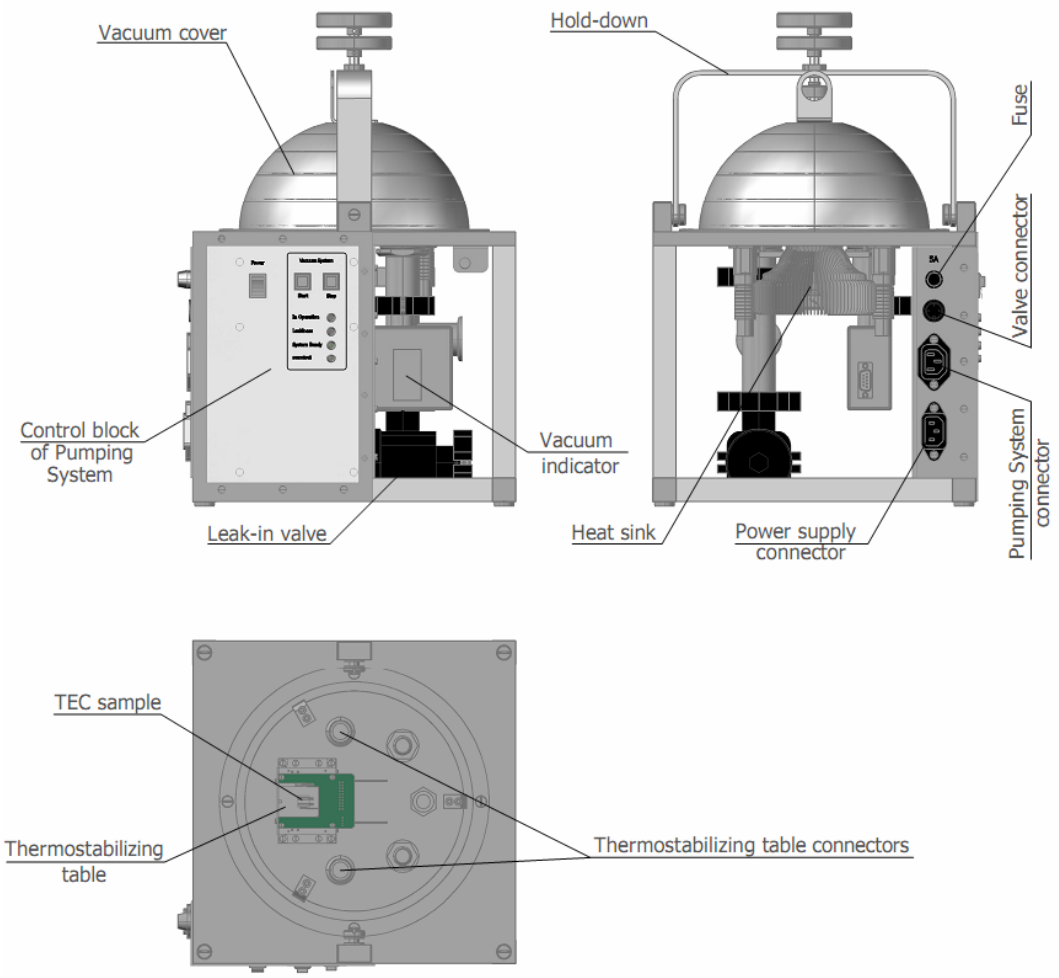
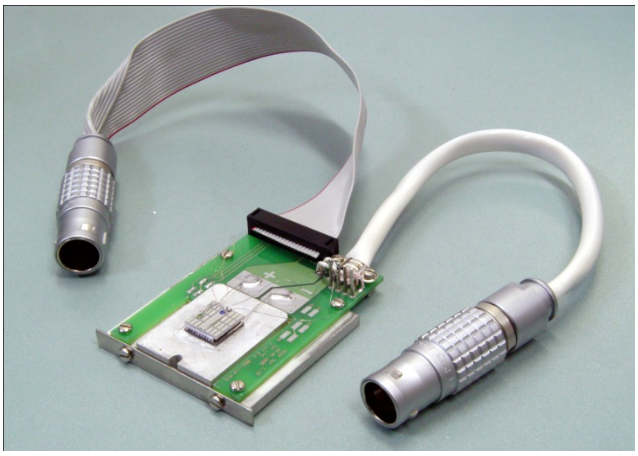


Figure 2.3-1



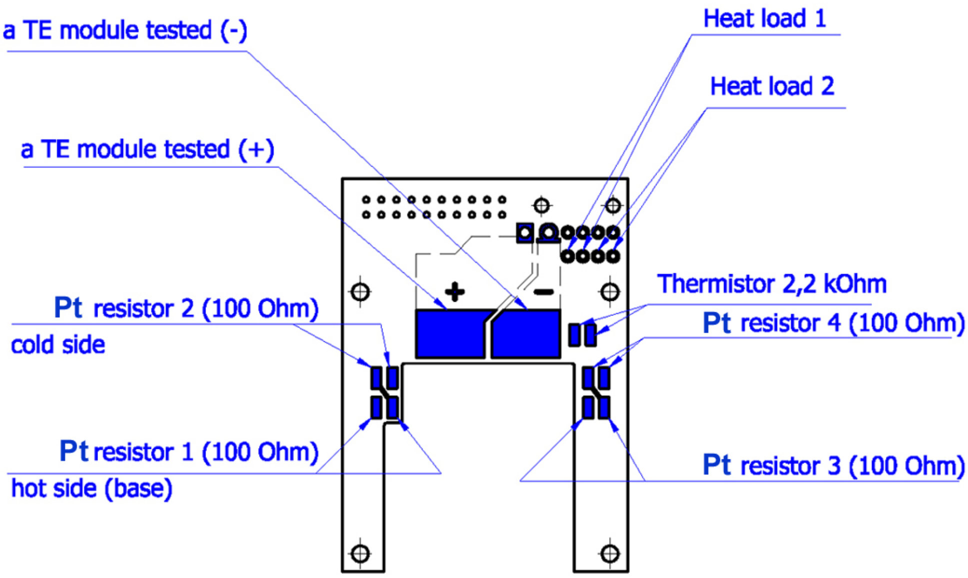


Figure 2.3-2

5) The leading wires of the testing circuits and the circuits of power supply of the thermostabillizing TE module as well as those of the tested TE module and of the heaters are soldered to the vacuum-tight connectors "Lemo".

6) The vacuum chamber is closed by the cover which is held down to the ring gasket.

7) The pumping is accomplished through the nipple by the pumping system Mini-TASK (see Figure 2.3-3).

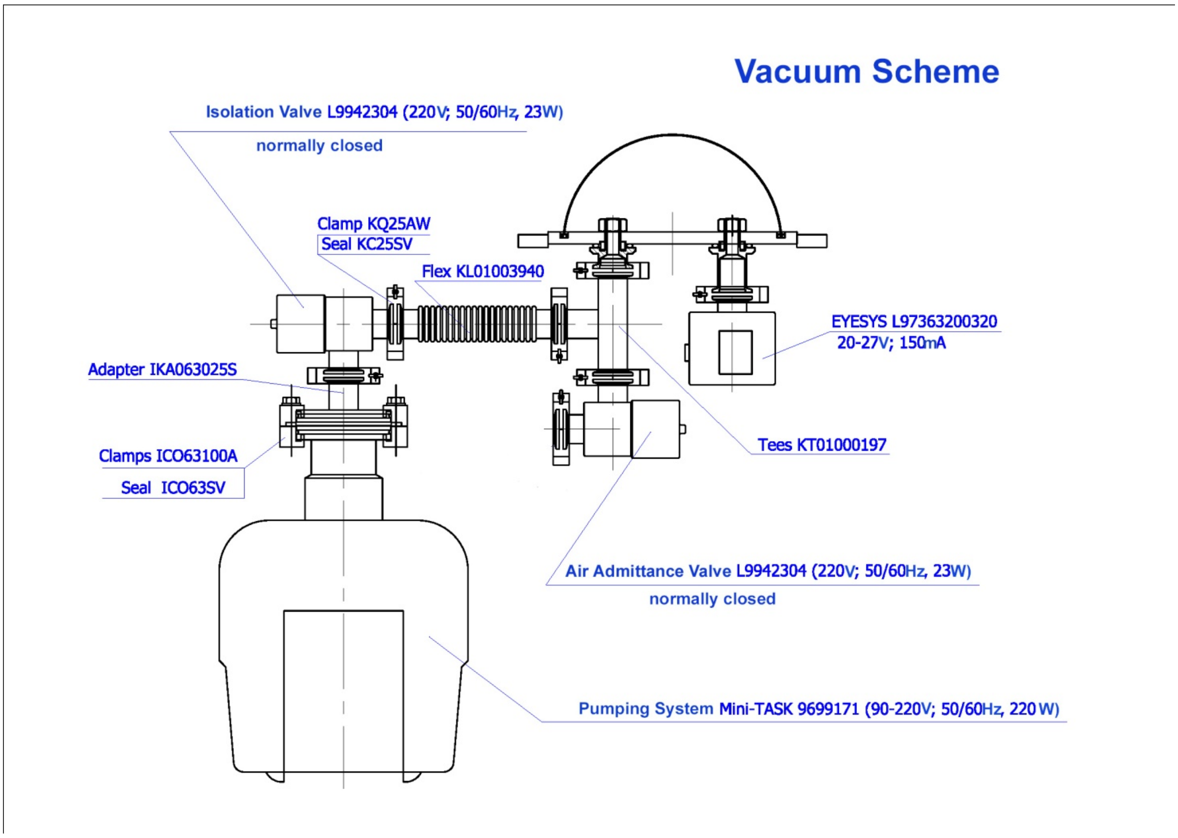


Figure 2.3-3

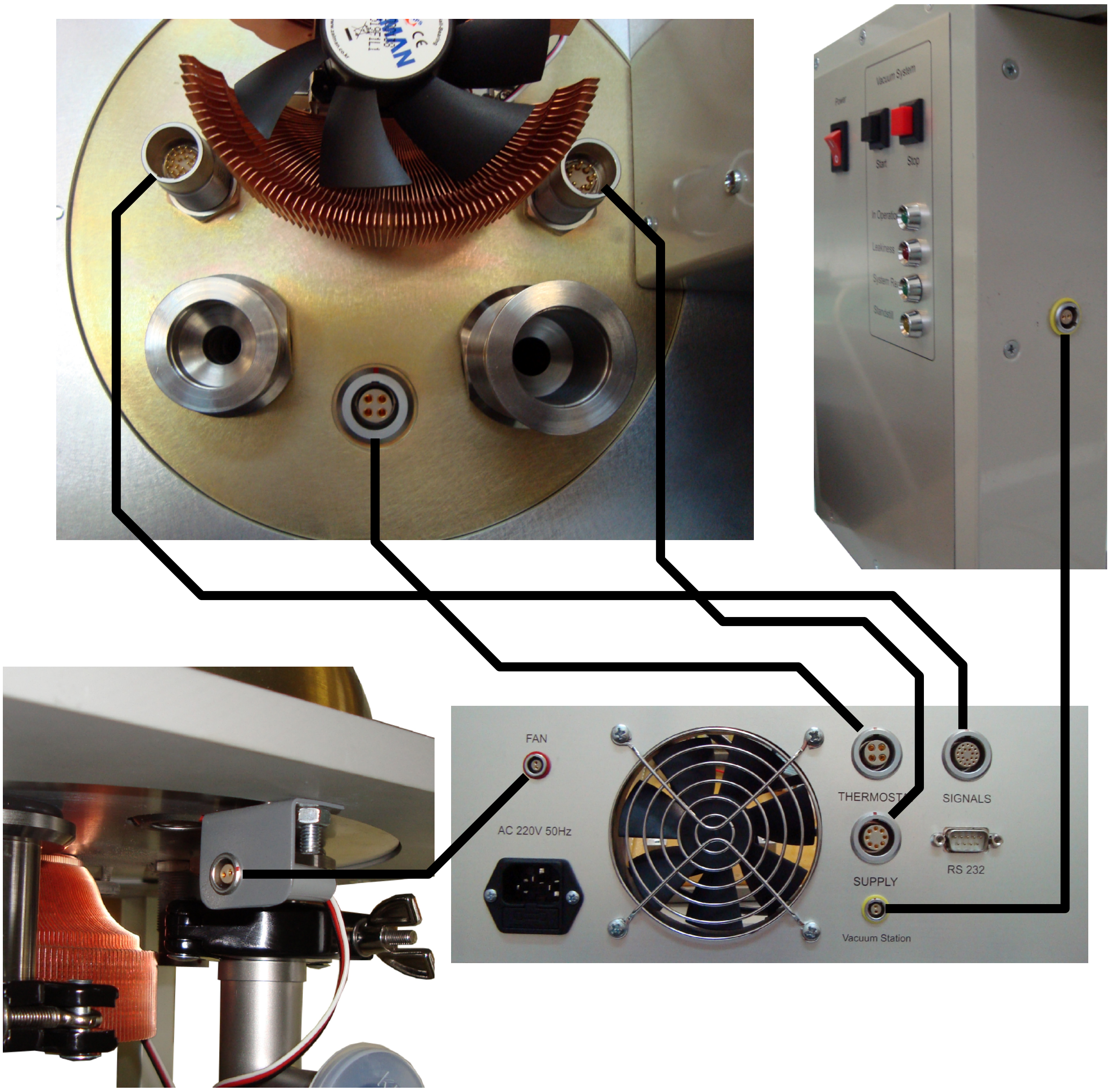
8) Residual gases level is controlled by the vacuum pressure gauge (EYESYS ConvecTorr).

9) The DX8020 control and signals processing is fulfilled by the control unit with the help of PC and the software "DX8020 Operation Program". The measuring methods and necessary mathematics are given hereinafter.

10) The temperature of the base and that of the tested TE module cold side is measured by platinum thermal resistors (Pt resistors, also temperature sensors or thermistors) of the nominal resistance 100 Ohm, type HEL-700-T-1-A. The measuring accuracy is ±0.3 °C.

2.3.1. Connection of Cables

All the connectors of the cables included in the kit are different, and allow an unambiguous connection.



2.3.2. How to Install TE Module to Be Tested

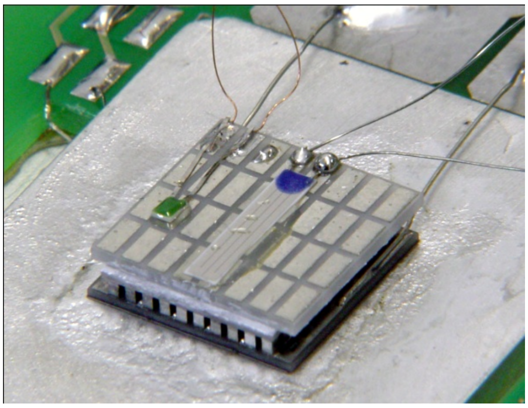
1) Prepare a TE module to be tested for measurement: identify the TE modules in the database or input the module data into the database if it is newly developed (see Section 3.5);

2) Mount the TE module to the substrate: apply either the solder 52%In-48%Sn (melting temperature 117ºC), or Rose's alloy (melting temperature 94ºC), or a thermal grease; use the solder Sn-63%, Pb-37% (melting temperature 183ºC) to connect the TE module wires outlets with the print circuit (observe the TE module polarity – see Figure 2.3-2.

IMPORTANT: It should be kept in mind that mounting by soldering provides more accurate test results. However we do not recommend soldering mounting for large TE modules (the linear dimensions exceeding 20 mm) to prevent effect of materials tempera-

ture expanding coefficients mismatch. Furthermore, it should be kept in mind that soldering is only possible for TE modules with outer surfaces metalized.

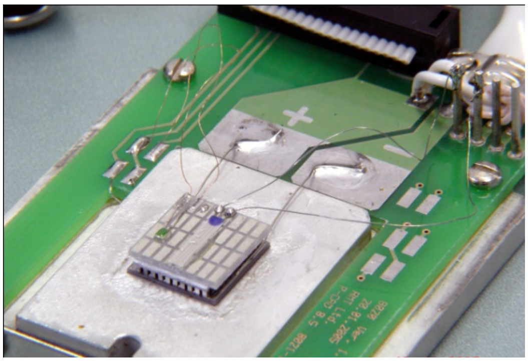
3) Use either the solder 52%In-48%Sn (melting temperature 117ºC), or Rose's alloy (melting temperature 94ºC), or a thermal grease to mount a ceramic or a copper substrate onto the TE module cold side, with a microheater and the temperature sensor (the platinum thermal resistor of the nominal resistance 100 Ohm, type HEL-700-T-1-A).



4) Solder the outlets of the temperature sensors (Pt resistors) and the wires of the heater on the print circuit of the sample holder according to the diagram given in Figure 2.3-2.

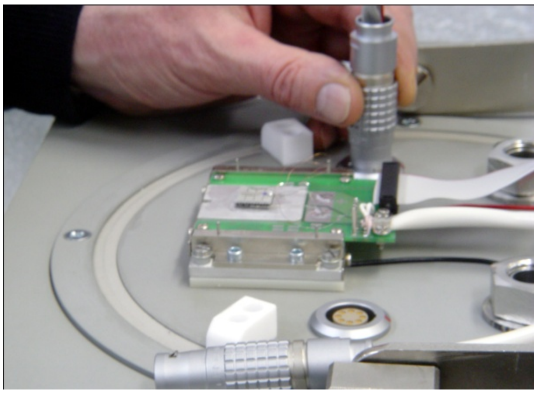
It should be borne in mind that thermistor 1 (see Figure 2.3-2) is used to measure the temperature of the base (the "hot" side of the module), and thermistor 2 (see Figure 2.3-2) - to measure the temperature of the "cold" side of the module.

Circuitry of the facilities is such that the thermistors work in pairs: One pair - thermistors 1 and 2, and another one - thermistors 3 and 4. When using only one additional thermistor 3 or 4, the contacts of another should be connected together (shorted).

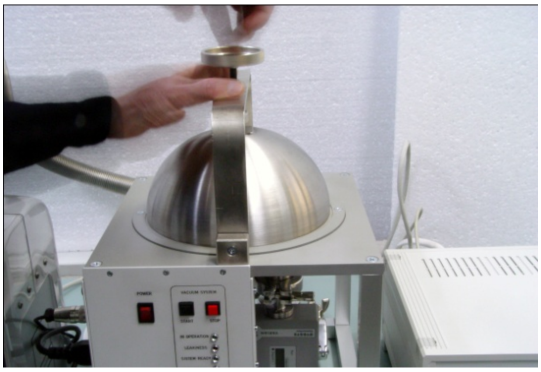


5) Insert the sample holder with the TE module mounted into the fastening guides of the vacuum table (Figure 2.3-1), pre-lubricating the mating surfaces with silicone oil.

6) Connect the connectors of the sample holder to the vacuum-tight connectors of the vacuum table.



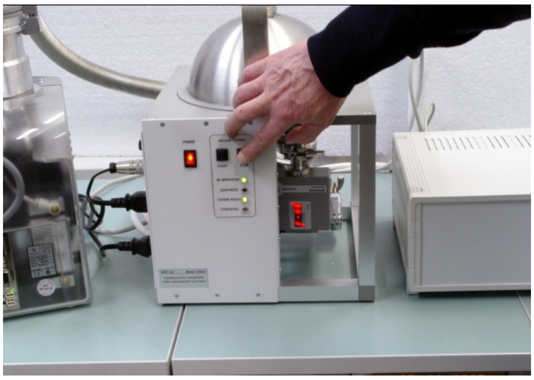
7) Close the table by the cover and press it to the gasket by the hold-down.



8) Turn on the vacuum-pump and pump out to residual pressure less than $1{\cdot}10^{-2}$ mm Hg (see Section 2.3.3).

9) Turn on the control unit and perform the tests according to the methods and software - see Chapters 3, 4.

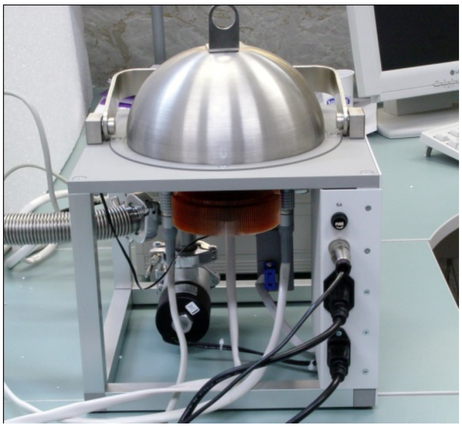
10) Having finished the tests, turn off the equipment, vacuum pump and let the air into the vacuum chamber (see Section 2.3.3).



2.3.3. Vacuum Pumping System Operation

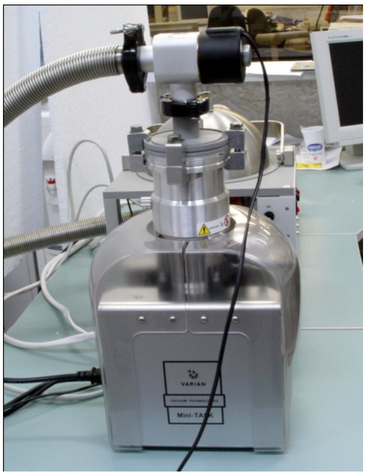
The vacuum pumping system should be assembled according to the scheme given in Figure 2.3-3.

How to switch the vacuum pumping system ON:



1) Connect by the cable the control block of the pumping system to the vacuum pumping system Mini-Task Mini-Task (Figure 2.3-1).

2) Connect by the cable the electromagnetic valve to the control block of the pumping system (Figure 2.3-1).



3) Plug the power supply cable into the control block of the pumping system.

4) Switch on the vacuum pumping system Mini-Task.

5) By the switch, switch on the control unit of the pumping system (the green light "In operation" is blinking).

6) Press the button "Start" on the control block of the pumping system (the green lamp "In operation" is on; the vacuum pumping system starts pumping the air out of the closed chamber).

7) If after 3.5 min the red lamp "Leakiness" is on, a leakiness is detected in the vacuum system. In this case the control block turns off the vacuum pumping system Mini-Task. It is possible to switch on the system again in 8 min. The leak should be stopped.

8) On the chamber pressure reaching 1x10^{-2} mm Hg the green lamp "System ready" is on and the equipment is ready for measurement (the pressure is indicated by the vacuum pressure gauge "Eyesys ConvecTorr").

How to switch the vacuum pumping system OFF:

1) After the measurements, press the "Stop" button and hold it down for a few seconds. The isolation valve closes on the system Mini-Task (Figure 2.3-3, valve #1) and the air admittance valve opens (Figure 2.3-3, valve #2).

2) The yellow lamp "Standstill" turns on. It is possible to switch on the system again by the button "Start" in 8 min after the lamp "Standstill" goes out.

2.4. 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) Once in a month control the data of the Pt resistors (temperature sensors) comparing them with the data of the standard thermometer. The admissible accuracy is ±0.3ºC.

3) Once in a month control the data of Z-meter by the standard resistors.the Pt resistors.

4) When in operation do not bar the vent-holes of the equipment DX8020 control unit.

3. DX8020 OPERATION PROGRAM

3.1. Program Preparation

3.1.1. 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.

To work with the program you need:

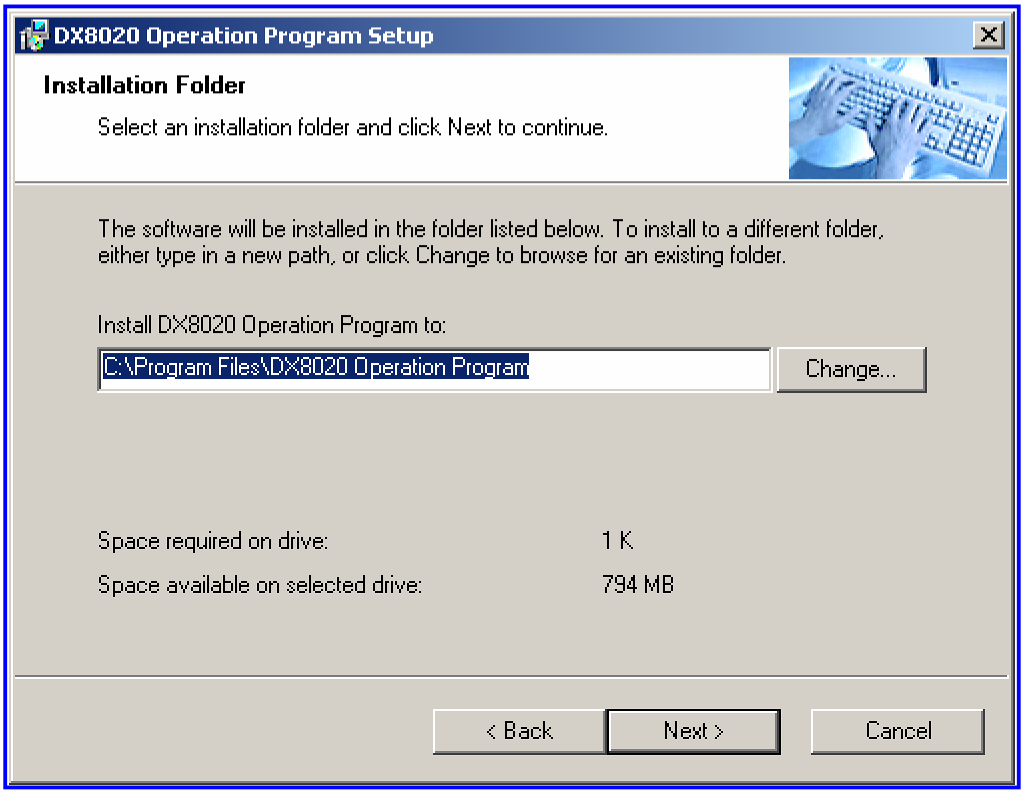
- IBM PC compatible computer with WINDOWS 98/2000/XP (2000/XP recommended);
- free serial port;
- 10 MB free disk space;
- 256 MB RAM.

The recommended screen resolution is 1024x768.

3.1.2. Program Installation

The program distributive is supplied on the CD delivered with the facilities.

Insert your CD into the appropriate drive and start the Setup program – Figure 3.1-1



DX8020 Operation Program Setup

Installation Folder

Select an installation folder and click Next to continue.

The software will be installed in the folder listed below. To install to a different folder, either type in a new path, or click Change to browse for an existing folder.

Install DX8020 Operation Program to:

C:\Program Files\DX8020 Operation Program

Space required on drive: 1 K

Space available on selected drive: 794 MB

Figure 3.1-1

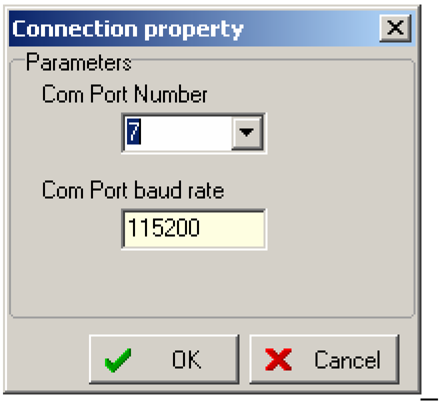
Follow all the installation steps. When the installation is over, the program icon will appear on the desktop and in the "**Start**" menu.

3.2. Connection

To connect with the device it is necessary:

- connect the device DX8020 and computer by the interface wire;
- 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.



Com Port Number: 7

Com Port baud rate: 115200

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

If the connection is successful, the status says "DX8020 ver. 100 found at COM1(2)"– Figure 3.2-1.

DX8020 ver. 100 found at com port 1.

Figure 3.2-1

If the connection fails, the message of an unsuccessful attempt to connect to the device appears – Figure 3.2-2.

DX8020 device not found. Check connection and communication parameters.

Figure 3.2-2

To solve this problem, follow these steps.

- 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 the program author.

3.3. Disconnection

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

3.4. Main Window "DX8020 Operation Program"

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

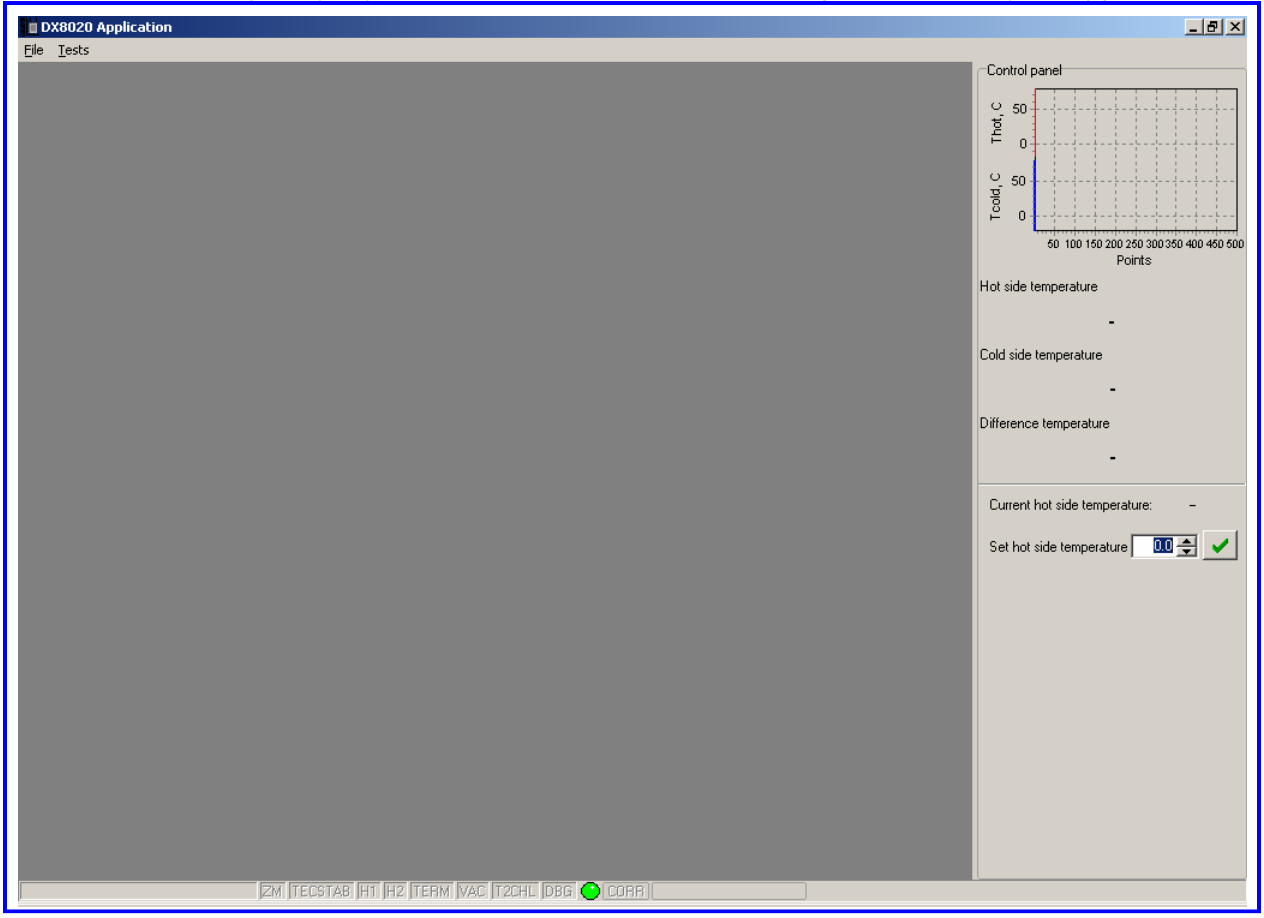


Figure 3.4-1

The main window can be divided into three fields.

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

Main Menu

The main menu structure is shown below.

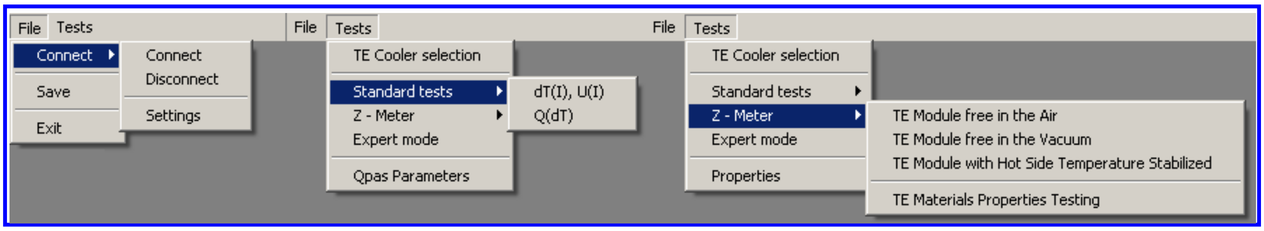
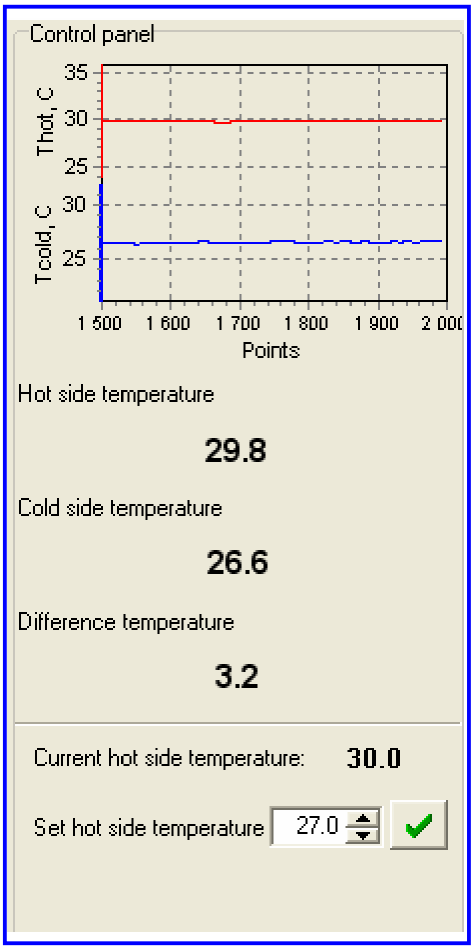


Figure 3.4-2

In the Z-Meter mode there is an additional menu item "Z-Meter History".

Figure 3.4-3

Temperature sensors panel is located in the right-hand part of the main window (see Figure 3.4-4).



Hot side temperature

29.8

Cold side temperature

26.6

Difference temperature

3.2

Current hot side temperature: 30.0

Set hot side temperature 27.0 ✓

Figure 3.4-4

The telemetry data from the sensors "T_1" (Hot side temperature) and "T_2" (Cold side temperature), as well as the difference between the two values is displayed continuously except the periods of measurement.

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

Status Panel

This panel is intended for the output of:

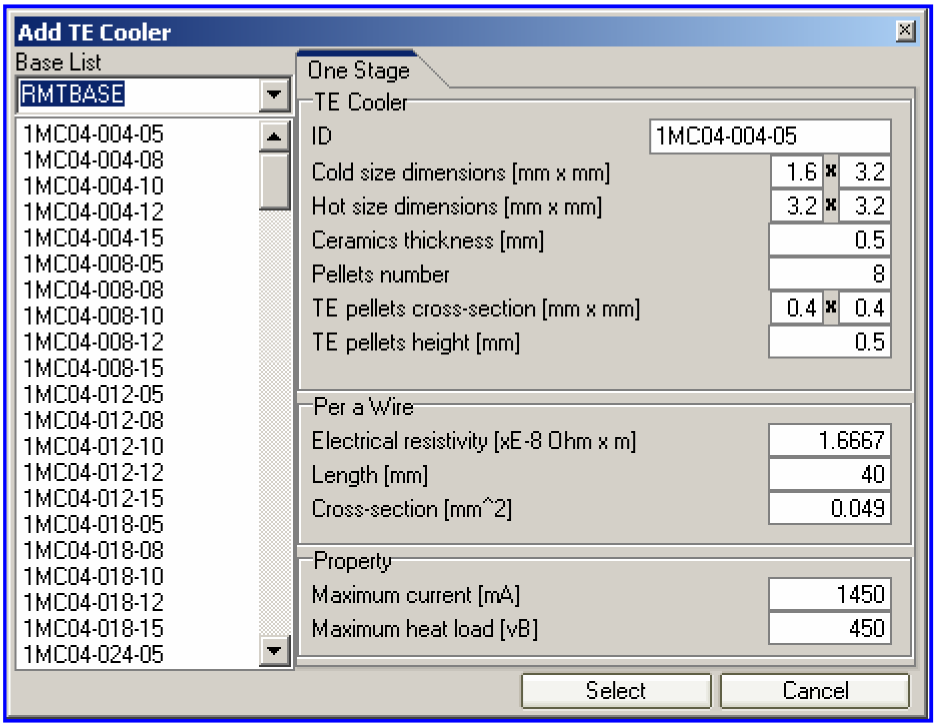
- device identification;
- device mode;
- temperature stabilization status;
- vacuum status;
- corrections status.

DX8020 ver. 100 found on 1 com port.

Figure 3.4-5

3.5. TE Module Selection from the Database

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:



Base List: RMTBASE

1MC04-004-05
1MC04-004-08
1MC04-004-10
1MC04-004-12
1MC04-004-15
1MC04-008-05
1MC04-008-08
1MC04-008-10
1MC04-008-12
1MC04-008-15
1MC04-012-05
1MC04-012-08
1MC04-012-10
1MC04-012-12
1MC04-012-15
1MC04-018-05
1MC04-018-08
1MC04-018-10
1MC04-018-12
1MC04-018-15
1MC04-024-05

TE Cooler

ID: 1MC04-004-05
Cold size dimensions [mm x mm]: 1.6 x 3.2
Hot size dimensions [mm x mm]: 3.2 x 3.2
Ceramics thickness [mm]: 0.5
Pellets number: 8
TE pellets cross-section [mm x mm]: 0.4 x 0.4
TE pellets height [mm]: 0.5

Per a Wire

Electrical resistivity [xE-8 Ohm x m]: 1.6667
Length [mm]: 40
Cross-section [mm^2]: 0.049

Property

Maximum current [mA]: 1450
Maximum heat load [vB]: 450

Figure 3.5-1

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

For adding a TE module not included it is necessary to choose "**USERBASE**" from combo box – see Figure 3.5-2.

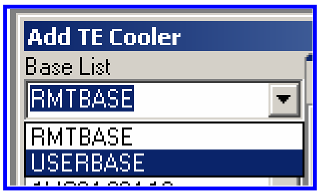


Figure 3.5-2

Then press the button "**New**" - Figure 3.5-3.

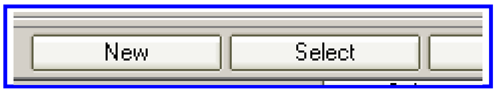
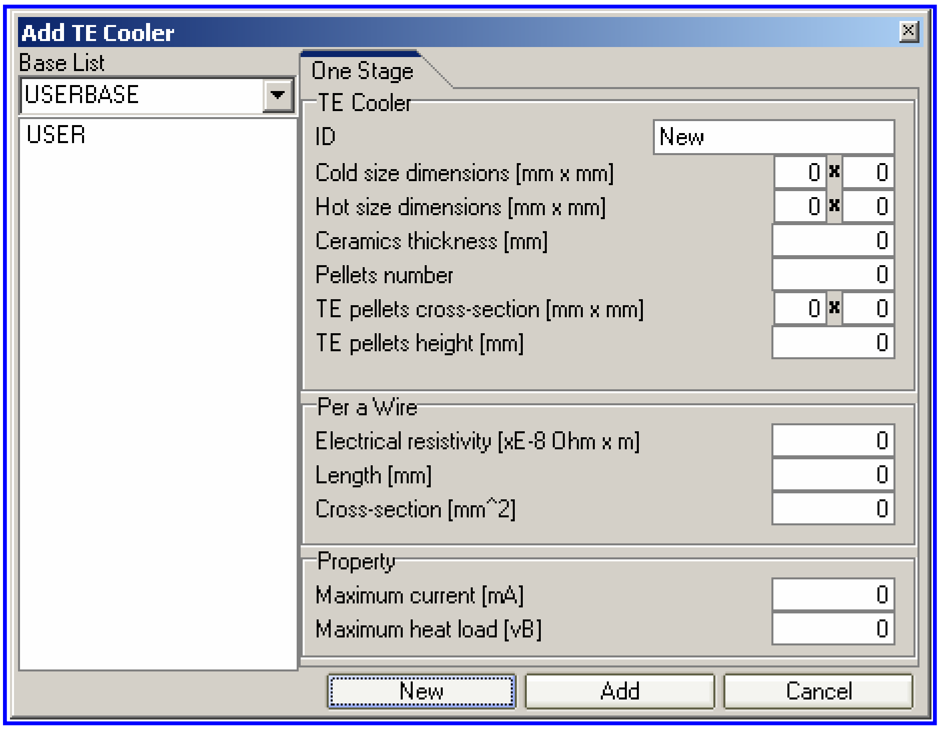


Figure 3.5-3

You are supposed to input the values of parameters required and save the new TE module specification pressing the button "**Add**" - Figure 3.5-4.



Base List: USERBASE

USER

TE Cooler

ID: New

Cold size dimensions [mm x mm]: 0 x 0

Hot size dimensions [mm x mm]: 0 x 0

Ceramics thickness [mm]: 0

Pellets number: 0

TE pellets cross-section [mm x mm]: 0 x 0

TE pellets height [mm]: 0

Per a Wire

Electrical resistivity [xE-8 Ohm x m]: 0

Length [mm]: 0

Cross-section [mm^2]: 0

Property

Maximum current [mA]: 0

Maximum heat load [vB]: 0

Figure 3.5-4

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.

4. MEASURING METHODS

The equipment DX8020 provide 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: ΔT(I), U(I);

1.2 At varied heat load at a certain electric current: Q(ΔT)

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

3. Z-R-τ 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. Testing of TE Materials PROPERTIES in a TE module (vacuum)

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

4.1. 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 2.2).

The characteristics measured in this mode are:

- **DT(I)** – temperature difference dependent on electric current at the cooling capacity Q=0. *The plot is used to obtain I_{max} and DT_{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(DT)** – 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 DT_{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 2.3.2, 3).

2) The TE module hot side is mounted onto the sample holder mounting surface (see Section 2.3.2, 2).

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 T_{hot} of the thermostabilizing surface is fixed within the range available (see **Table 2.2**).

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.

4.1.1. Measurement of DT(I), U(I) at Q=0

This mode is to enable building the dependences of the TE module temperature difference DT and the voltage U on electric current I, as well as obtaining the values $DT_{max}(I_{max})$, U_{max}, I_{max} *– see Section Mathematical Annex VI*. Measurement of Imax, ΔTmax.

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 T_{hot}.

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

3) Set the limiting testing electric current values (see *Mathematical Annex VI*. Measurement of Imax, ΔTmax);

4) Set the electric current step.

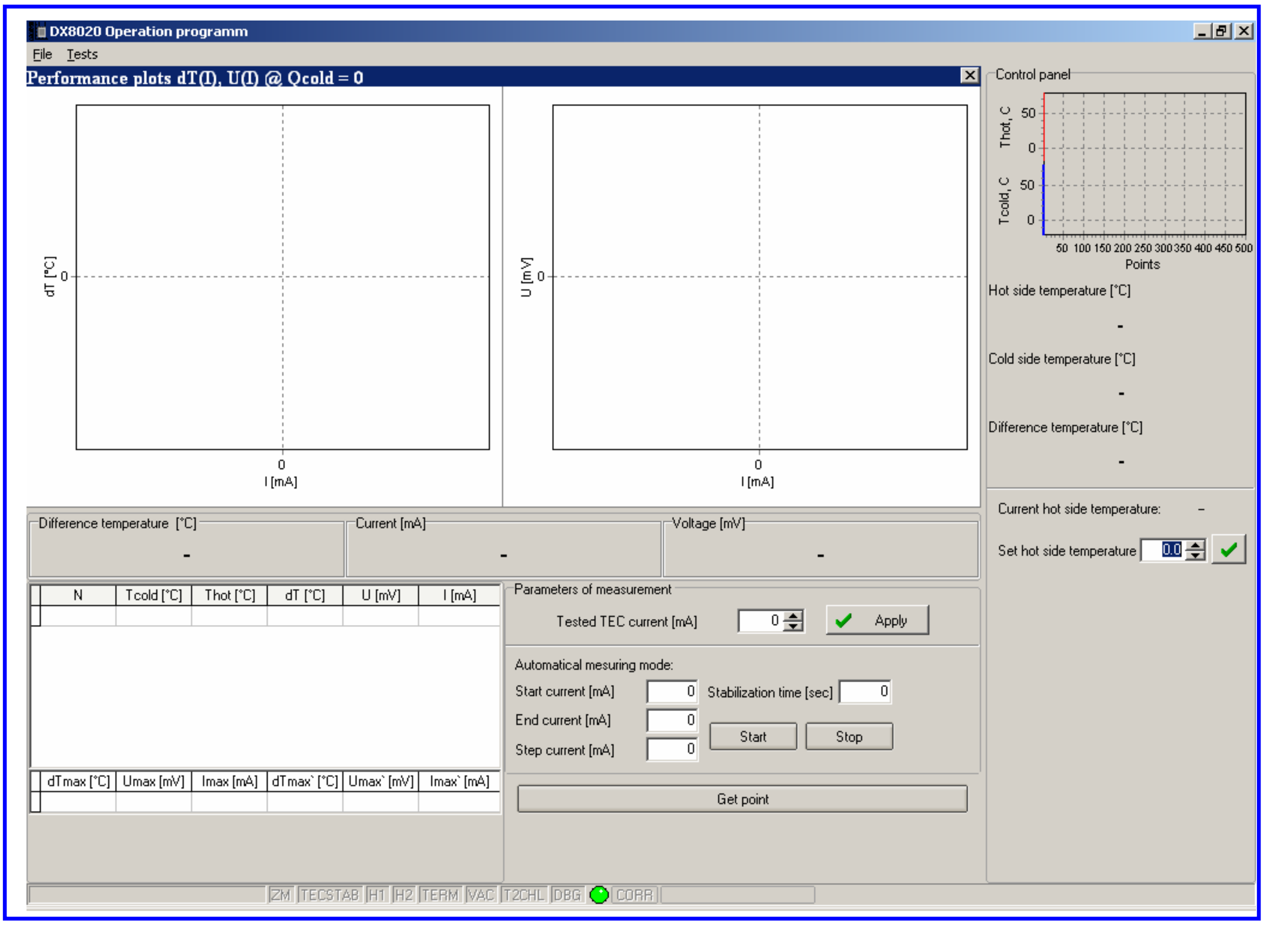
5) Start measuring. Consistently the TE module is fed by a constant electric current, beginning from ΔI, TE module is maintained at a given current during t_{stab} to achieve steady-state.

6) For each electric current value I the TE module temperature difference ΔT(I) and voltage U(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 ΔT(I) are processed; the values I_{max}, U_{max}, ΔT_{max} are calculated with no corrections applied (see *Mathematical Annex VI*. Measurement of Imax, ΔTmax).

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 (Figure 4.1-1).

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"**.



Current hot side temperature: –

Set hot side temperature 0.0

Tested TEC current [mA] 0

Start current [mA] 0

Stabilization time [sec] 0

End current [mA] 0

Step current [mA] 0

Figure 4.1-1

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 in Figure 4.1-2.

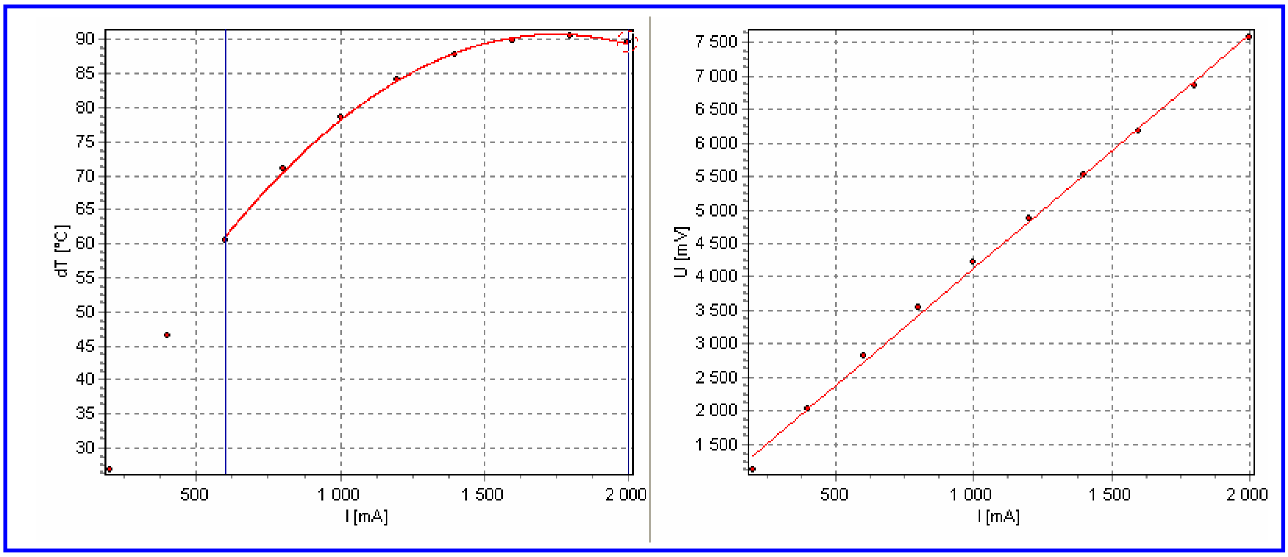
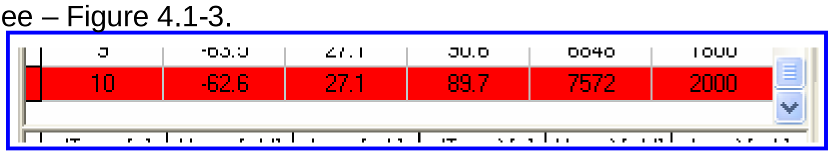


Figure 4.1-2

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 colour in the summary table, see – Figure 4.1-3.



10	-62.6	27.1	89.7	7572	2000

Figure 4.1-3

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 – Figure 4.1-4.

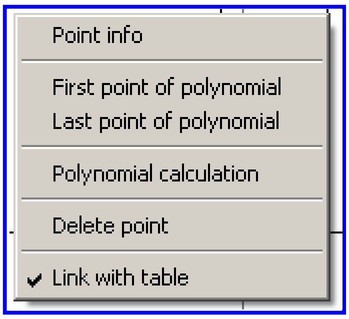
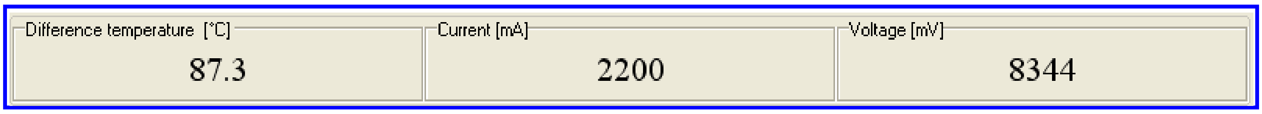


Figure 4.1-4

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.



Difference temperature [°C] 87.3

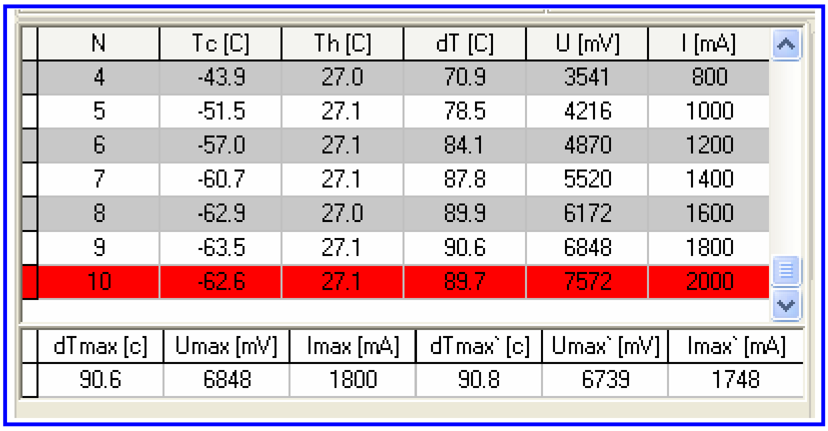
Current [mA] 2200

Voltage [mV] 8344

Figure 4.1-5

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 dTmax, Imax, Umax and the values dTmax, Imax, Umax 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

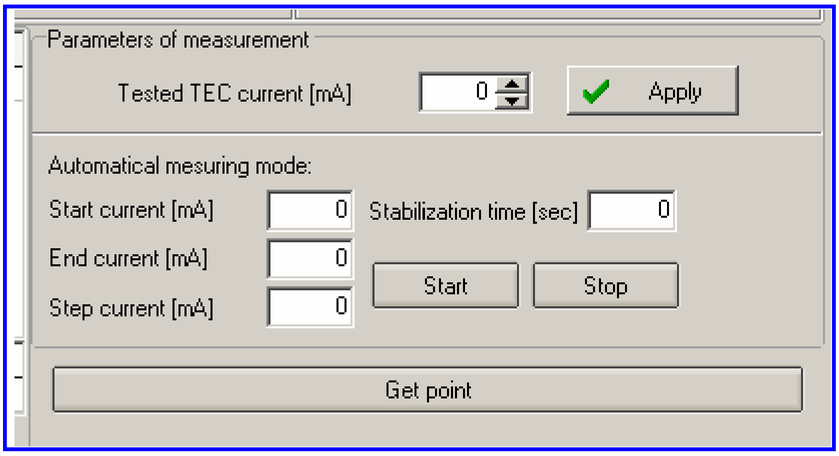
dTmax [c]	Umax [mV]	Imax [mA]	dTmax` [c]	Umax` [mV]	Imax` [mA]
90.6	6848	1800	90.8	6739	1748

Figure 4.1-6

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

Control Panel

This field allows control of the testing procedure.



Parameters of measurement

Tested TEC current [mA] 0

Automatical mesuring mode:

Start current [mA] 0

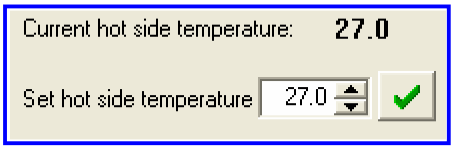
Stabilization time [sec] 0

End current [mA] 0

Step current [mA] 0

Figure 4.1-7

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



Current hot side temperature: **27.0**

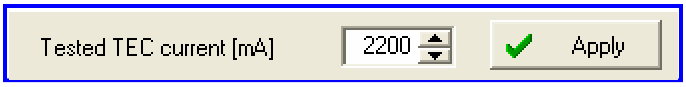
Set hot side temperature 27.0

Figure 4.1-8

The test can be done either manually or automatically.

Testing Manually

Set the electric current value and click "apply", see Figure 4.1-9.



Tested TEC current [mA] 2200

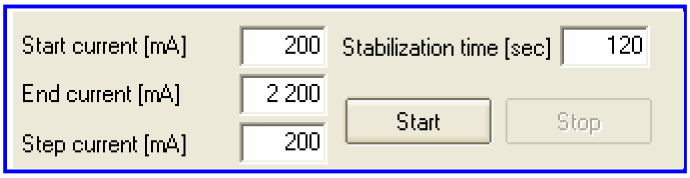
Figure 4.1-9

After achieving a steady-state temperature of the module cold side press the button "**Get point**" – see Figure 4.1-10.

Figure 4.1-10

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 – Figure 4.1-11.



Start current [mA] 200

End current [mA] 2 200

Step current [mA] 200

Stabilization time [sec] 120

Figure 4.1-11

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 dTmax, Umax, Imax and the values dTmax, Umax, Imax 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 dTmax, Umax, Imax can be obtained more exactly.

4.1.2. Measurement of Q(DT)

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 Qmax and extracting the corrected value dTmax at the given current. See *Mathematical Annex VII.* Qmax Measurement and ΔTμαξ 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 T_{hot}.

2) Choose the TE module stabilization time 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 ΔT(I), U(I) at Q=0), either by calculation.

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

$$Q_{lim} = \frac{1}{2} Q_{max}, \qquad (4.1.1)$$

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

5) At the given current the TE module temperature difference ΔT is measured for 5 values of the heater power: Q=(0, 0.25, 0.5, 0.75, 1)Q_{lim}. For each measurement the TE module stabilization time is t_{stab}.

6) Build the curve Q(ΔT) by the measured points using linear interpolation (*See Mathematical Annex VII.* Qmax Measurement and ΔTμαξ Correction).

7) For each measured ΔT at the given current I the correction for the passive heat load from the wires is calculated:

$$Q_{pas}(\Delta T) = Q_{wire}(\Delta T) \qquad (4.1.2)$$

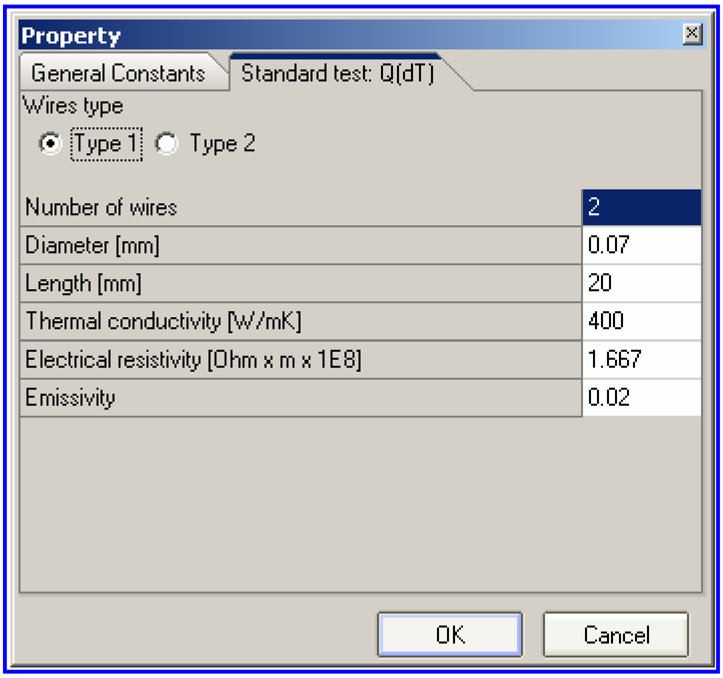
(see *Mathematical Annex IV.* Passive Heat Flux along the Leading Wires).

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

9) Find Q_{max}, ΔT_{max} at a given current (see *Mathematical Annex VII. Qmax Measurement and DTmax Correction*)

10) Find Q'_{max}, $\Delta T'_{max}$ at a given current (see *Mathematical Annex VII. Qmax Measurement and DTmax Correction*).

IMPORTANT: 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", Bocused bookmark "Standard test : Q(dT)" see Figure 4.1-12.



Wires type

● Type 1 ○ Type 2

Number of wires	2
Diameter [mm]	0.07
Length [mm]	20
Thermal conductivity [W/mK]	400
Electrical resistivity [Ohm x m x 1E8]	1.667
Emissivity	0.02

Figure 4.1-12

The wires are divided into two types:

- Type 1 - Wire Pt resistor;
- Type 2 - wire heater.

To enter the measurements of Q (dT), must choose the "Main Menu" - "Tests" - "Standard tests" - "Q (dT)". Window measurements looks as shown in Figure (Figure 4.1-13).

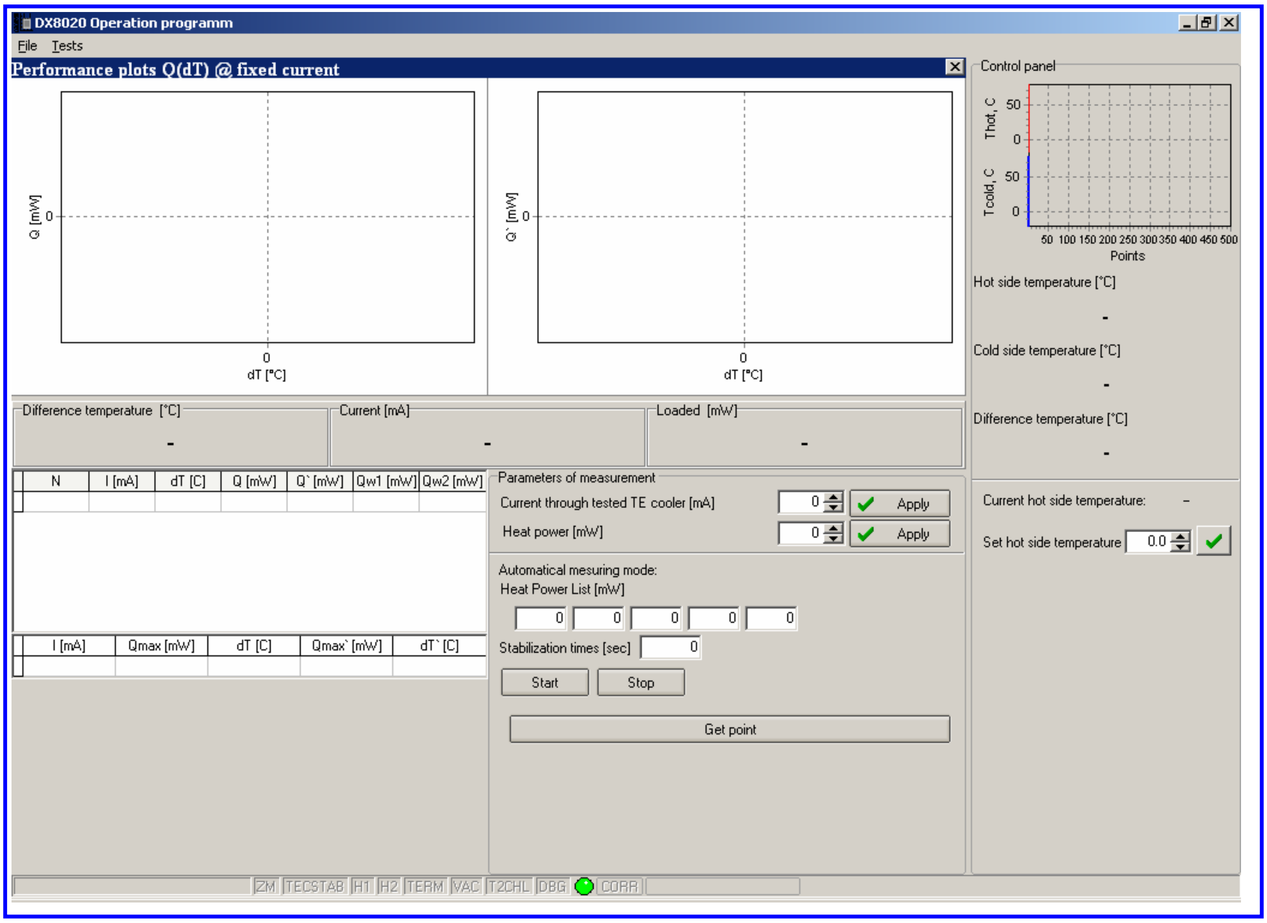


Figure 4.1-13

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 taking into account passive heat flows through the wires (see Figure 4.1-14).

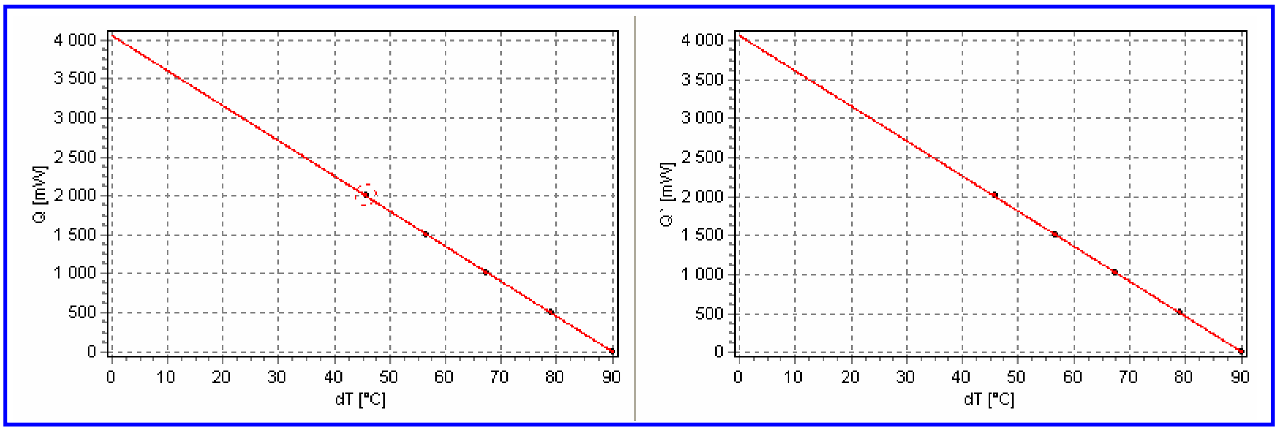
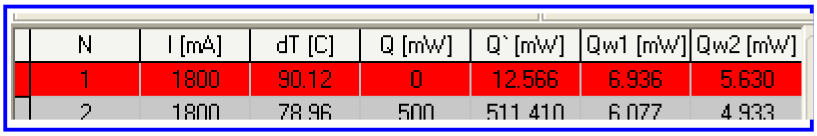


Figure 4.1-14

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 colour in the table – see Figure 4.1-15.



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

Figure 4.1-15

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 – Figure 4.1-16.

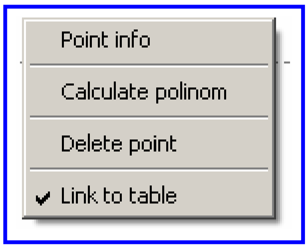
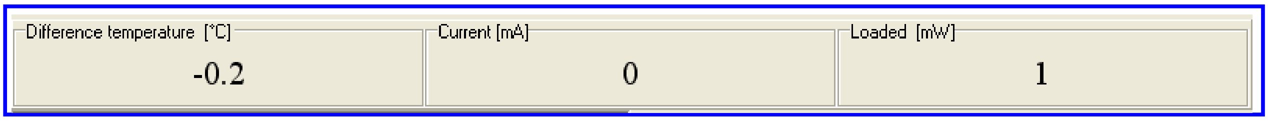


Figure 4.1-16

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.



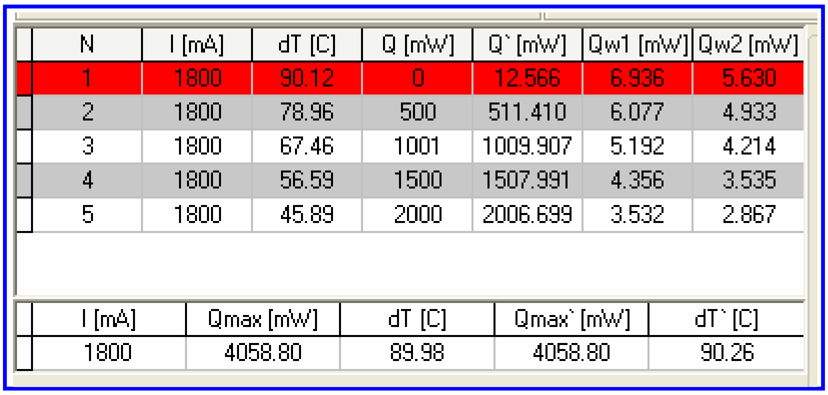
Difference temperature [°C]	Current [mA]	Loaded [mW]
-0.2	0	1

Figure 4.1-17

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 Qmax, dTmax with no corrections applied and Qmax’, dTmax’ corrected by the passive heat load – Figure 4.1-18.



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

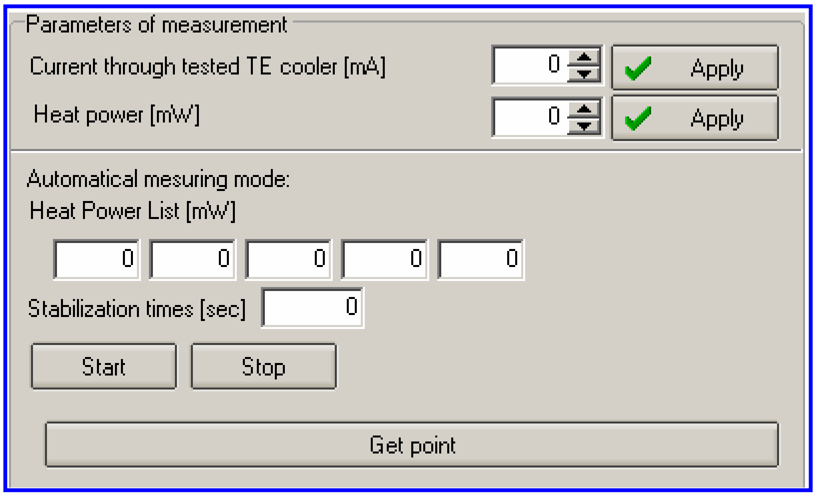
I [mA]	Qmax [mW]	dT [C]	Qmax` [mW]	dT` [C]
1800	4058.80	89.98	4058.80	90.26

Figure 4.1-18

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

Control Panel

This field allows control of the testing procedure – see Figure 4.1-19.



Parameters of measurement

Current through tested TE cooler [mA] 0

Heat power [mW] 0

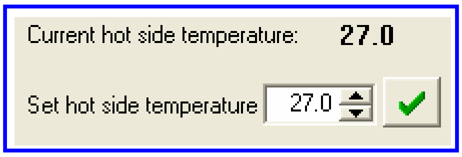
Automatical mesuring mode:

Heat Power List [mW] 0 0 0 0 0

Stabilization times [sec] 0

Figure 4.1-19

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 (Figure 4.1-20).



Current hot side temperature: 27.0

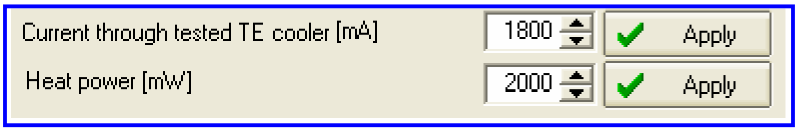
Set hot side temperature 27.0

Figure 4.1-20

The test can be done either manually or automatically.

Testing Manually

Set the electric current and heat load values and click "apply" – Figure 4.1-21.



Current through tested TE cooler [mA] 1800

Heat power [mW] 2000

Figure 4.1-21

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

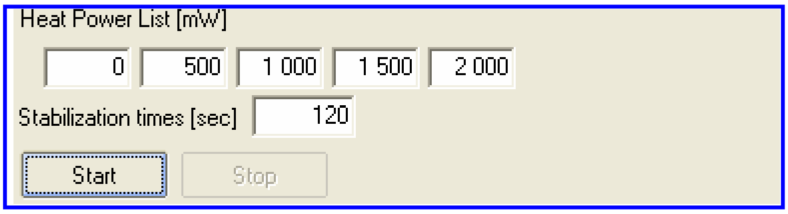
Testing Automatically

Set the electric current value and click “apply" – Figure 4.1-22.

Current through tested TE cooler [mA] 1800

Figure 4.1-22

Set the hot side stabilization time and 5 values of the heat to be pumped – see Figure 4.1-23.



Heat Power List [mW]

0	500	1 000	1 500	2 000

Stabilization times [sec] 120

Figure 4.1-23

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 Qmax, dTmax with no corrections applied and Qmax', dTmax' corrected by the passive heat load are displayed.

4.2. 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 2.3.2); ; the heater power equals the necessary value;

2) The TE module hot side is mounted onto the sample holder mounting surface (see Section 2.3.2);

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 T_{hot} of the thermostabilizing surface is fixed within the range available (see Table 2.1);

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 T_{hot};

2) Set the required heat load Q_0 (the heater power);

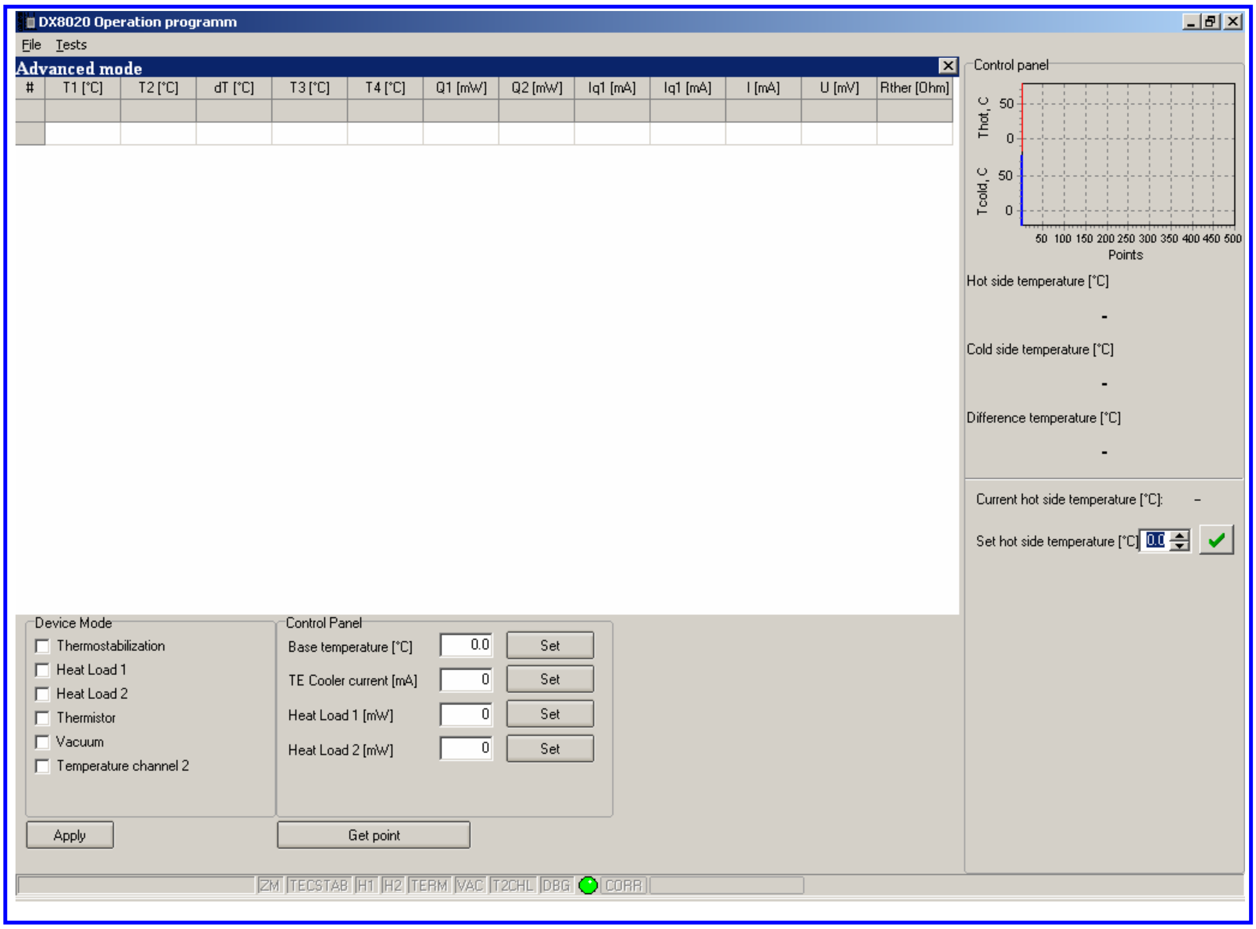
3) Set the required electric current I_0;

4) Wait until the thermostabilizing is steady, observing the stabilizing temperature data;

5) Measure the temperature difference ΔT of the TE module at the given values Q_0 and I_0;

IMPORTANT. In order 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**". The window can be viewed in Figure 4.2-1.



Hot side temperature [°C] -

Cold side temperature [°C] -

Difference temperature [°C] -

Current hot side temperature [°C]: –

Set hot side temperature [°C] 0.0

☐ Thermostabilization
☐ Heat Load 1
☐ Heat Load 2
☐ Thermistor
☐ Vacuum
☐ Temperature channel 2

Base temperature [°C] 0.0
TE Cooler current [mA] 0
Heat Load 1 [mW] 0
Heat Load 2 [mW] 0

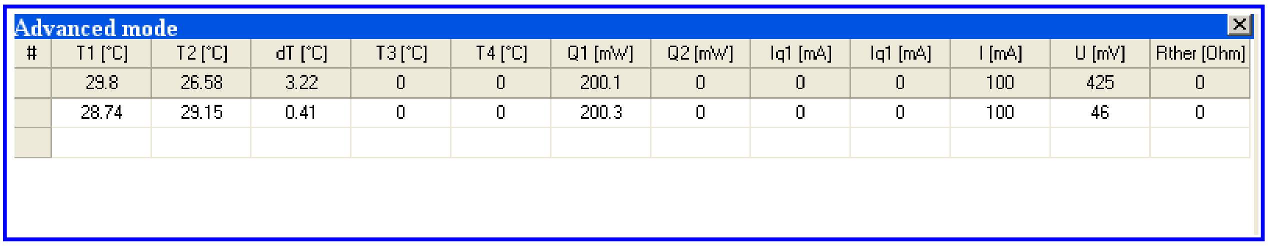
Figure 4.2-2

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) – see Figure 4.2-3.

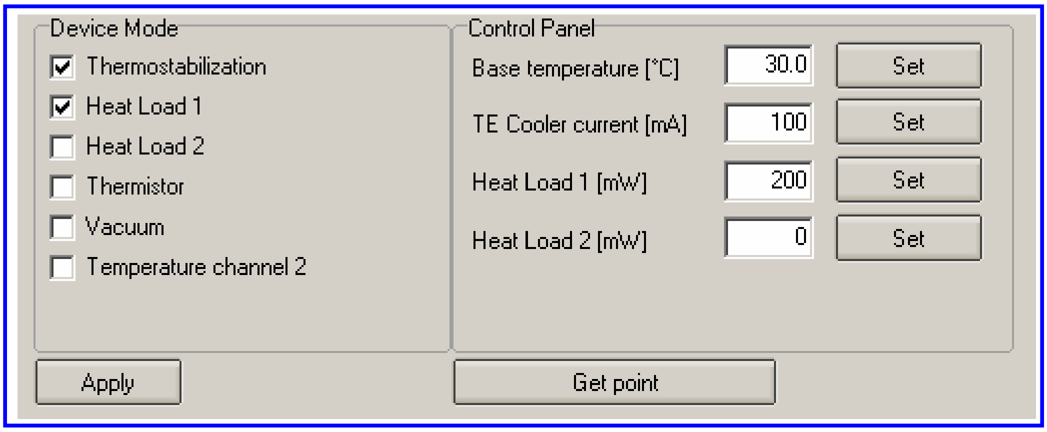


#	T1 [°C]	T2 [°C]	dT [°C]	T3 [°C]	T4 [°C]	Q1 [mW]	Q2 [mW]	Iq1 [mA]	Iq1 [mA]	I [mA]	U [mV]	Rther [Ohm]
	29.8	26.58	3.22	0	0	200.1	0	0	0	100	425	0
	28.74	29.15	0.41	0	0	200.3	0	0	0	100	46	0

Рисунок 4.2-4

Control Panel

In this field you may change the device mode and set the parameters at which the TE module is to be tested – Figure 4.2-5.



Device Mode

☑ Thermostabilization
☑ Heat Load 1
☐ Heat Load 2
☐ Thermistor
☐ Vacuum
☐ Temperature channel 2

Control Panel

Base temperature [°C] 30.0
TE Cooler current [mA] 100
Heat Load 1 [mW] 200
Heat Load 2 [mW] 0

Figure 4.2-6

For example, in the figure given (Figure 4.2-6), 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 30 ºC, TE module electric current is 100 mA, the heater is 200 mW.

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

4.3. Z-R-t-Metering

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

Similar to the series of Z-R-τ meters developed by RMT for complex express testing the facilities 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-τ meters are to be followed (see *Mathematical Annex VIII.* Measurement of TE Module Figure-of-Merit). The methods of the DX8020-100 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 t

For brevity we call Z-R-τ-Meter as Z-Meter.

4.3.1. 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, τ of a TE module at room temperature ~ 300 K;
- ensure a correlation between measurements of Z, R, τ 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 DX8020-100 cover is closed.

5) For testing in vacuum the chamber is pumped out to residual pressure not exceeding $1\cdot10^{-2}$ 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 $I_{test}=0.01I_{max}$ (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 $U_\alpha(t)_\pm$ is displayed;

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

$$U_\alpha(t)_\pm = Ust_{\alpha\pm}(1-e^{-t/\tau_\pm}); \tag{4.3.1.1}$$

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

IMPORTANT: To proceed with the Z-R-τ-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:

$$U_{R\pm} = \frac{1}{10}\sum_{i\geq(N-10)}\left(U(t_i)_\pm - U_\alpha(t_i)_\pm\right); \tag{4.3.1.2}$$

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

$$Z\pm = \frac{1}{T_a}\frac{Ust\,\alpha_\pm}{U_{R_\pm}}; \tag{4.3.1.3}$$

Then the average Z is calculated as:

$$Z_{av} = \frac{1}{2}(Z_+ + Z_-); \tag{4.3.1.4}$$

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).

IMPORTANT: The corrections are only applied to the value Z_{av}:

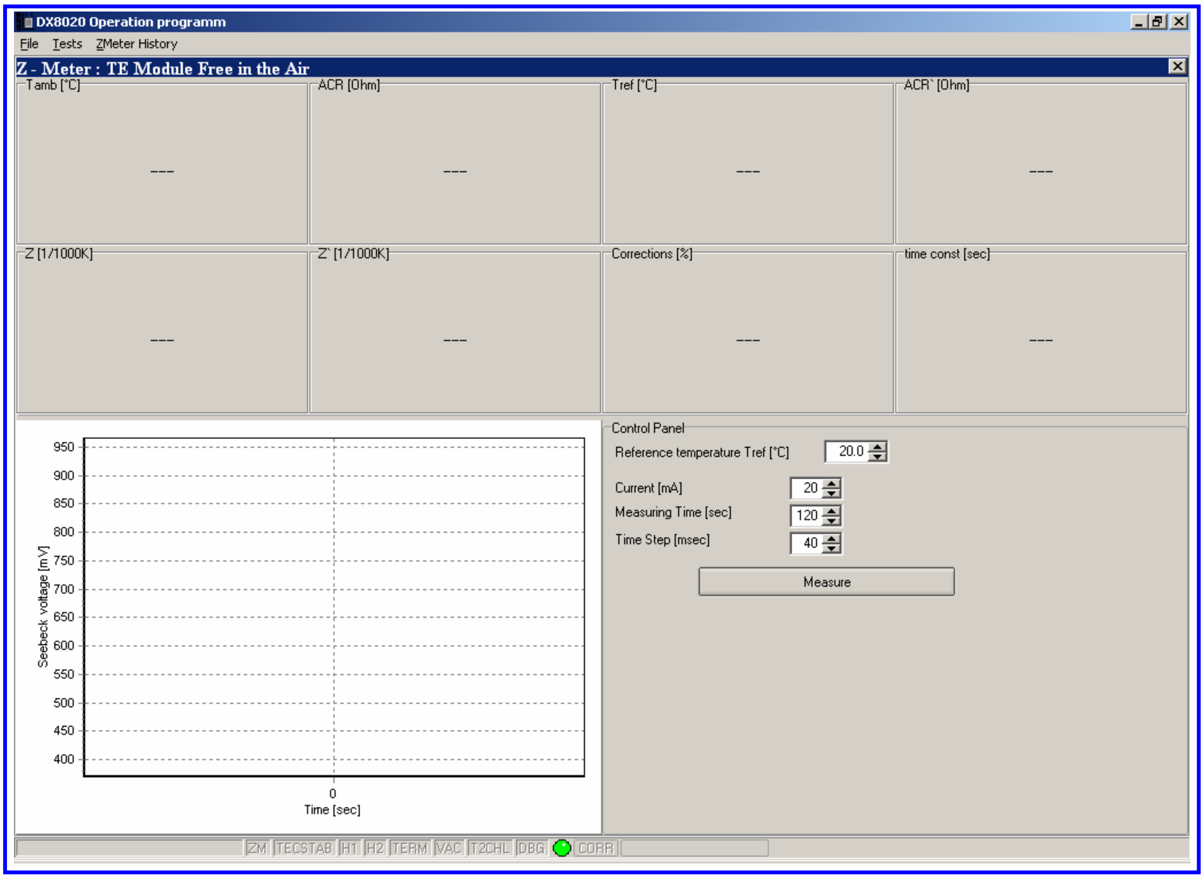
$$Z'_{av} = \frac{Z_{av}}{(1+b_T)}\left(1+b_{th}\right)\left(1+b_r\right) \tag{4.3.1.5}$$

Therefore the whole correction can be written as:

$$corr = \frac{\left(1+b_{th}\right)\left(1+b_r\right)}{1+b_T}, \tag{4.3.1.6}$$

All the expressions for the corrections are given in *Mathematical Annex VIII.* Measurement of TE Module 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 in Figure 4.3-1.



Tamb [°C] ---
ACR [Ohm] ---
Tref [°C] ---
ACR` [Ohm] ---
Z [1/1000K] ---
Z` [1/1000K] ---
Corrections [%] ---
time const [sec] ---

Control Panel
Reference temperature Tref [°C] 20.0
Current [mA] 20
Measuring Time [sec] 120
Time Step [msec] 40

Figure 4.3-2

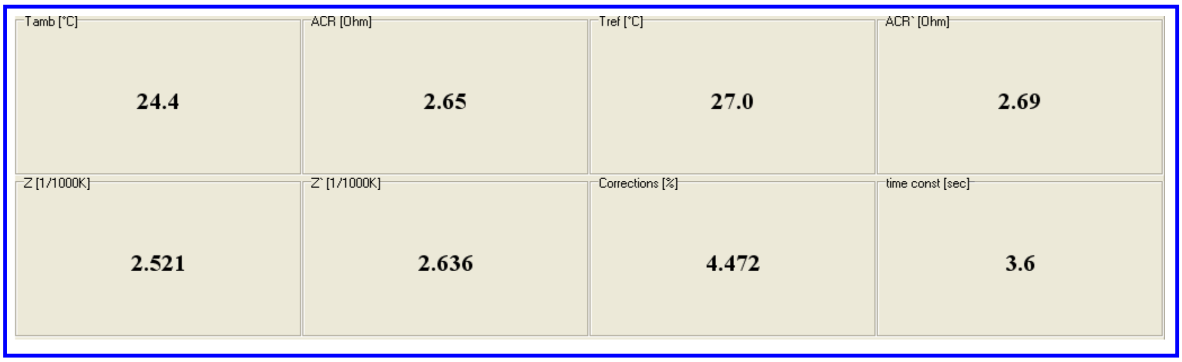
The window consists of three fields:

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

Results Field

This field is shown in

Figure 4.3-3.



Tamb [°C] 24.4
ACR [Ohm] 2.65
Tref [°C] 27.0
ACR` [Ohm] 2.69
Z [1/1000K] 2.521
Z` [1/1000K] 2.636
Corrections [%] 4.472
time const [sec] 3.6

Figure 4.3-3

The following results are displayed:

- Tamb – ambient temperature;
- ACR – TE module electrical resistance (alternating current);
- ACR` – ACR referred to Tref;
- 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 behaviour of the Seebeck voltage

This curve (see Figure 4.3-4) displays the dynamics of the Seebeck voltage at the test current of two polarities. Each experimental curve is accompanied by the interpolation one.

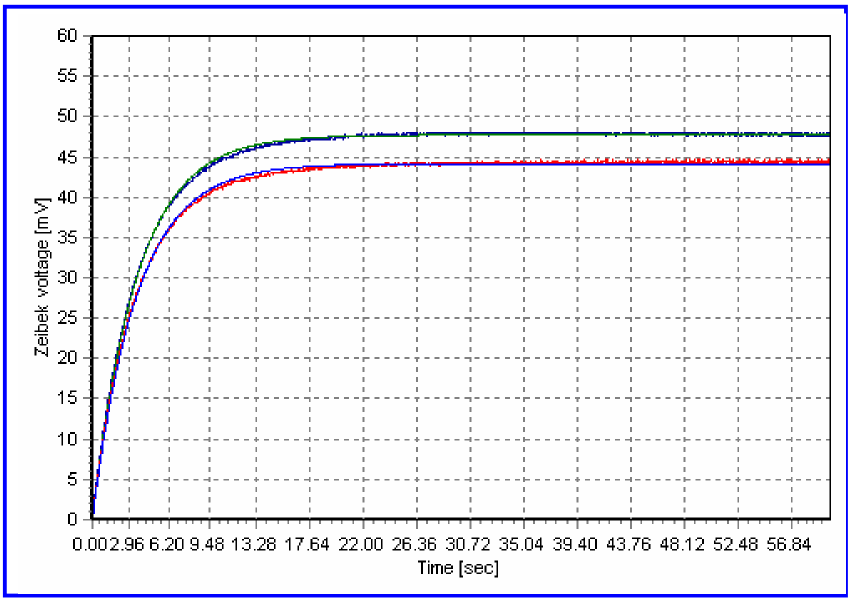
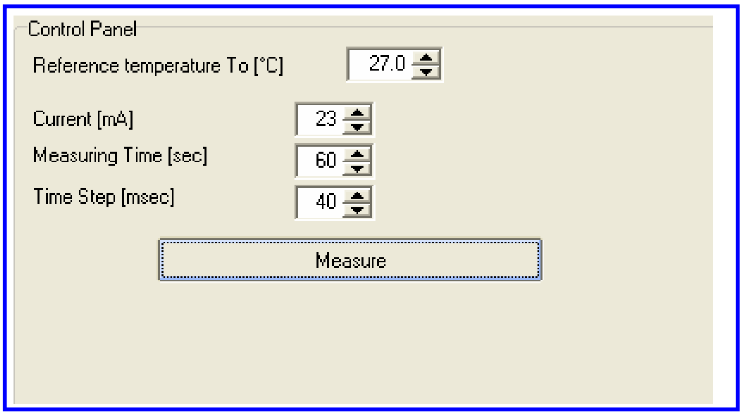


Figure 4.3-4

Control Panel

The control panel allows setting the measurement parameters – see (Figure 4.3-5).



Control Panel

Reference temperature To [°C] 27.0

Current [mA] 23

Measuring Time [sec] 60

Time Step [msec] 40

Figure 4.3-5

The following parameters are to be set:

- Reference temperature (Tref) – temperature ACR is referred to;
- Current – TE module electric current (0.01Imax is recommended);

- Measuring Time;
- Time Step (recommended to increase for longer testing).

4.3.2. TE Module with the Hot Side Temperature Stabilized

The mode is intended for Z-R-τ- testing of a TE module at the given temperature. *See* Mathematical Annex VIII. *Measurement of TE Module 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 **How to Install TE Module to Be Tested** Section 2.3.2).

2) The TE module leading wires are soldered onto the connecting plates.

3) The thermostabilizing TE module is on. The thermostabizing surface temperature T_{hot} is fixed within the range available (see Table 2.2);

4) The DX8020-100 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:

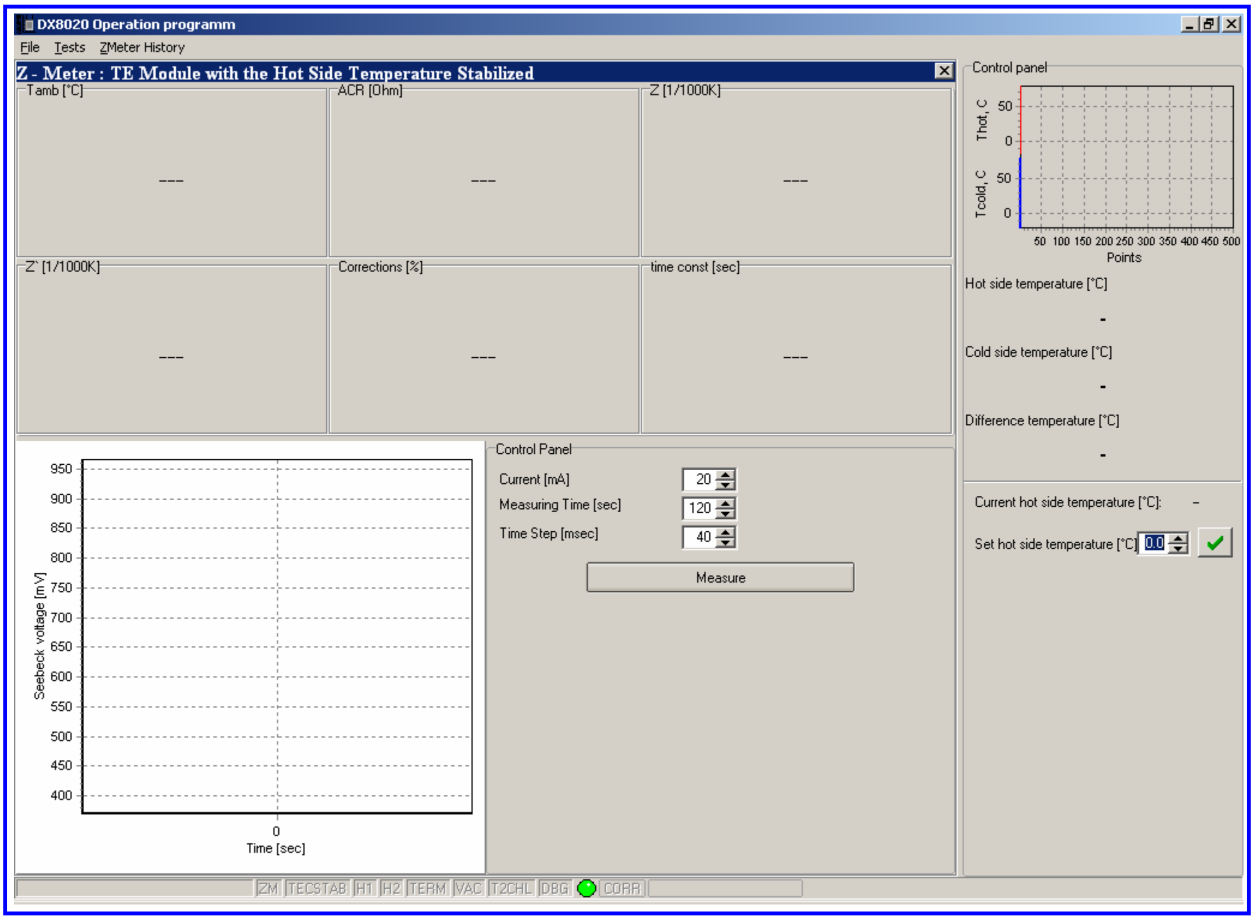
1) Set the temperature of the thermostabilizing surface T_{hot}; wait until the thermostabilizing is steady.

2) The measurements 2) – 5) of Section 4.3.1. Eq. (4.3.1.3) is modified as:

$$Z_{\pm} = \frac{1}{T_{hot}} \frac{U_{st}\alpha_{\pm}}{U_{R_{\pm}}}; \tag{4.3.2.1}$$

The value Z is measured and corrected (see *Mathematical Annex VIII.* Measurement of TE Module Figure-of-Merit) for a TE module with T_{hot}=const. The corrections only include the leading wires correction (see *Mathematical Annex IV.* Passive Heat Flux along the Leading Wires) and radiation (see *Mathematical Annex II.* Estimation of Radiation Heat Exchange Coefficient*, Mathematical Annex III.* Additional Thermal Conductance between Pellets).

Choose the command "**Main Menu**"-"**Tests**"-"**Z-meter**"-"**TE module with the Hot Side Temperature Stabilized**". The measurement window is shown in Figure 4.3-6.



Current [mA] 20

Measuring Time [sec] 120

Time Step [msec] 40

Set hot side temperature [°C] 0.0

Figure 4.3-6

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-τ-Meter for TE Module Free (air/vacuum)".

4.4. TE Properties Testing

This testing mode enables experimental estimate of TE matrials 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 T_{hot}.

2) The TE module leading wires are soldered onto the connecting plates.

3) The thermostabilizing TE module is on. The thermostabizing surface temperature T_{hot} is fixed within the range available (see Table 2.2);

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 T_{hot}; wait until the thermostabilizing is steady.

2) Repeat the Z-R-τ-metering of the TE module with the hot side temperature T_{hot} stabilized; the values of AC R and Z of the TE module are found (with / with no corrections applied.

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

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

$$\text{b. } \rho = R_{pellet}\frac{s}{l}, \qquad (4.4.1)$$

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

Here N is the TE module pellets number. The electrical resistance R_{me} is calculated as:

$$R_{me} = \rho_{Cu}\frac{d + 2/3w}{wl_{me}}, \qquad (4.4.2)$$

where d is the distance between pellets of the TE module, w is their width, l_{me} is the metal junctions thickness.

4) By the known polynomial temperature dependence $\kappa=1/2(\kappa_n+\kappa_p)$ the Seebeck coefficient is calculated by:

$$\alpha = \sqrt{\frac{Z\kappa}{\sigma}}\,; \qquad (4.4.3)$$

The corrected parameter α corresponds to the corrected Figure-of-Merit Z.

Among the three parameters α, σ, κ the parameter κ is the least sensitive to charge carriers properties, that is why a standard $\kappa(T)$ can serve for estimating the coefficient α. In Figure 4.4-1 the dependence $\kappa(T)$ averaged for n- and p-type room temperature optimized TE materials is given. This curve is a default function the DX8020-100 software offers.

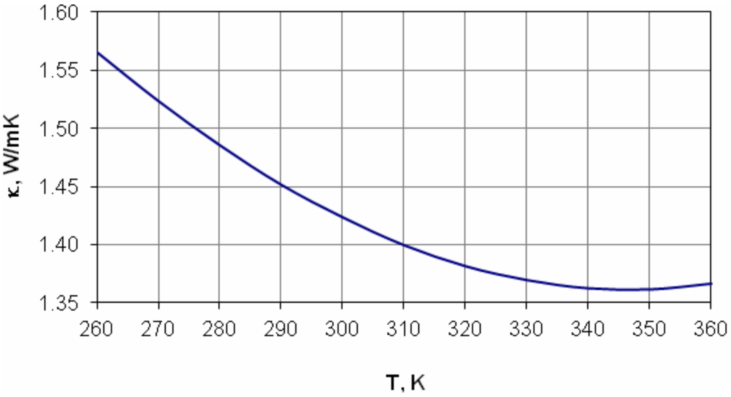
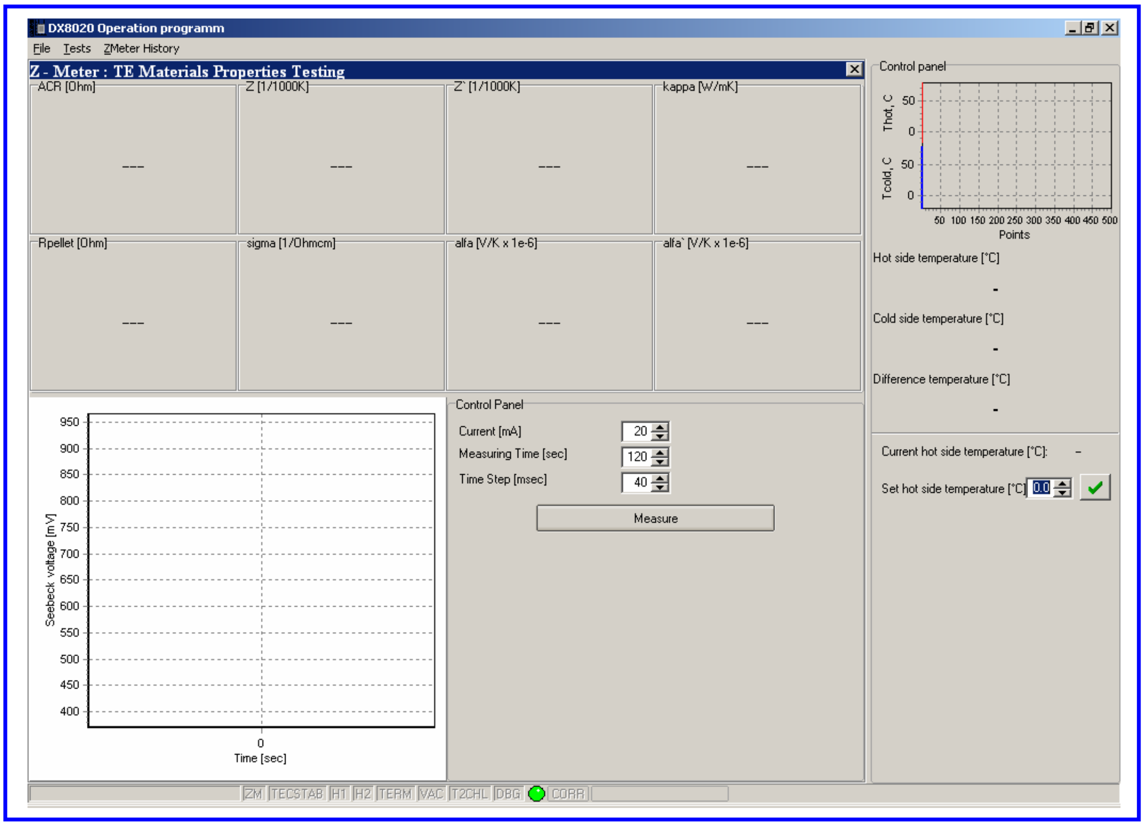


Figure 4.4-1

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 measurement window is shown in (Figure 4.4-2).



Current [mA] 20

Measuring Time [sec] 120

Time Step [msec] 40

Current hot side temperature [°C]: -

Set hot side temperature [°C] 0.0

Figure 4.4-2

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

5. *Mathematical Annex I.* Estimation of Convectional Heat Exchange Coefficient

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

$$\alpha_{conv} = \frac{\kappa}{x} Nu \, , \ Nu = C(Gr\,Pr)^n \qquad (5.1)$$

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

The Grashof number is described as:

$$Gr = \frac{g\beta\Delta T x^3}{\nu^2} \, , \qquad (5.2)$$

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

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

$$Pr = \frac{\nu}{a} \, , \qquad (5.3)$$

$$a = \frac{\kappa}{c_p \rho} \, , \qquad (5.4)$$

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

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

$$\alpha_{conv} = \frac{\kappa}{x} 0.75 (Gr\,Pr)^{0.25} \qquad (5.5)$$

Table 5.1 offers dry air parameters at normal pressure and temperature 20 °C and 30 °C.

Table 5.1

T, °C	r, kg/m ^{3}	c_p, J /(kg • K)	κ, W/(m • K)	$n \cdot 10^6$, 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 ΔT=3K (approximately true in Z-metering). In Table 5.2 the estimates for α_{conv} are given for some TE modules in the air at 20 °C.

Table 5.2

TE module type	$x \cdot 10^3$, m	a_{conv}, W/m^{2}K (20°C)
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:

$$Q_{pas\ conv} = \alpha_{conv} F_1 \Delta T \tag{5.6}$$

6. *Mathematical Annex II*. Estimation of Radiation Heat Exchange Coefficient

We designate:

"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:

$A_1=0.8$ (common for ceramics)

$A_2=0.45$ (common for stainless steel).

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

$$A_{12}=\frac{1}{\frac{1}{A_1}+\frac{F_1}{F_2}\left(\frac{1}{A_2}-1\right)} \tag{6.1}$$

For micro modules $F_2 \ll F_1$ and effective emissivity nearly coincides with the value 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:

$$\alpha_{rad}=\sigma_{SB}A_1(T_{hot}^2+T_{cold}^2)(T_{hot}+T_{cold}), \tag{6.2}$$

where σ_{SB} is the Stefan-Boltzmann constant.

For testing a TE module in the Z-R-τ-metering option, free heat exchange mode the value α_{rad} equals the following:

$$\alpha_{rad}=4\sigma_{SB}A_1T_a^3, \tag{6.3}$$

For testing a TE module in the Z-R-τ-metering option and the base side temperature stabilized at T_{hot}, the value α_{rad} is defined via T_{hot}:

$$\alpha_{rad}=4\sigma_{SB}A_1T_{hot}^3. \tag{6.4}$$

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

$$Q_{pas\ conv}=\alpha_{rad}F_1\Delta T \tag{6.5}$$

7. *Mathematical Annex III*. Additional Thermal Conductance between Pellets

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

$$\kappa' = \kappa(1 + b_{th}), \qquad (7.1)$$

where κ is 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:

$$b_{th} = B_{air} + B_{rad}, \qquad (7.2)$$

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

Introduce β as the pellets filling coefficient:

$$\beta = \frac{ns}{S}, \qquad (7.3)$$

where n is the pellets number, s is a pellet cross-section, S is the cold substrate surface.

The value B_{air} is calculated as:

$$B_{air} = \frac{\kappa_{air}}{\kappa}\left(\frac{1}{\beta} - 1\right), \qquad (7.4)$$

The correction for radiation can be written as:

$$\boldsymbol{B_{rad}} = \frac{l}{\kappa}\gamma\sigma_{SB}\left(\frac{1}{\beta} - 1\right)(T_{hot} + T_{cold})(T^2{}_{hot} + T^2{}_{cold}) \qquad (7.5)$$

where σ_{SB} is the Stefan-Boltzmann constant, γ is emissivity of the inner side of the TE module substrate; T_{hot} is the hot side temperature, T_{cold} is the cold side temperature.

For small electric currents (for example while measuring Z) $T_{hot} \approx T_{cold} \approx T_a$, and formula (III.5) can be rewritten as:

$$\boldsymbol{B_{rad}} = \frac{4l}{\kappa}\gamma\sigma_{SB}\left(\frac{1}{\beta} - 1\right)T_a^3 \qquad (7.6)$$

In **Table 7.1** we give the calculated results for B_{air} and B_{rad} for typical TE modules at T_a=293 K for typical temperature of Z,R,τ-metering: T_{hot} =293 K, T_{cold} =290 K (ΔT=3 K).

Table 7.1

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

8. *Mathematical Annex IV*. Passive Heat Flux along the Leading Wires

Consider a wire with no insulation, the cross-section is S, the length is L, the cross-section perimeter is U. Let α 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:

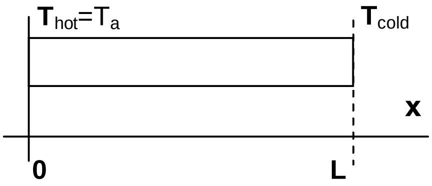


Figure 8-1

$$\kappa\frac{d^2T(x)}{dx^2}+j^2\rho+A(Ta-T(x))=0\,, \tag{8.1}$$

where κ is the wire material thermal conductivity, ρ is its electrical resistivity, T(x) is temperature in the coordinate x. The value A is defined as:

$$A=\alpha\frac{U}{S} \tag{8.2}$$

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

$$T(x)\big|_{x=0}=T_{hot}\ ,\ T(x)\big|_{x=L}=T_{cold} \tag{8.3}$$

The heat flux arriving at the cold end equals

$$Q=-\kappa S\frac{dT}{dx}\bigg|_{x=L} \tag{8.4}$$

Solving Eq. (8.1) we find the temperature distribution along the wire:

$$T(x)=T_a-\frac{j^2\rho}{A}\left(e^{px}-1\right)+\left\{\frac{j^2\rho}{A}\left(e^{px}-1\right)-\Delta T\right\}\frac{sh(px)}{sh(pL)}\,, \tag{8.5}$$

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

The passive heat flow onto the cold end is yielded (8.4) and (8.5):

$$Q_{pas}=S\sqrt{A\kappa}\left[\frac{j^2\rho}{A}e^{pL}+\left\{\frac{j^2\rho}{A}\left(1-e^{pL}\right)+\Delta T\right\}\frac{ch(pL)}{sh(pL)}\right], \tag{8.6}$$

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

$$\alpha_{rad}=\gamma\sigma_{SB}(T_{av}+T_a)(T^2av+T^2a)\,, \tag{8.7}$$

where $T_{av}=1/2(T_{hot}+T_{cold})$, σ_{SB} is 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 DX8020-100 methods the corrections on the passive heat flow along the wires are taken into account for the TE module cold side only (no corrections for intermediate substrates). There may be two different types of these wires:

1) Resistor wires (Pt);

2) Heater wires.

Consider exemplary calculations for both the types.

1) The common parameters of thermoresistor wires: the material is copper, κ=400 W/mK, $\rho=1.667\cdot10^{-8}$ Ohm·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=20ºC. The hot end temperature $T_{hot}=T_a$. The cold end temperature T_{cold} is -50 °C (approximate minimal temperature of a single-stage TE module cold substrate at I_{max} and T_a=20ºC). The heat exchange for the wire surface is that of radiation. For copper we take the value of emissivity γ=0.02 (polished copper). Then the heat exchange coefficient α equals $\alpha = 0.095$ W/(m^2·K).

At the small current (here $\frac{j^2\rho}{A} << \Delta T$, $\frac{j^2\rho}{A} \sim 0.173$) and if the wire thermal conductance is high enough while the radiation heat exchange from the surface is low: pL<<1 (here the value pL is equal to 0.16), the temperature distribution along the wire is nearly linear – in Figure 8-2 you are given the results of the exact calculation:

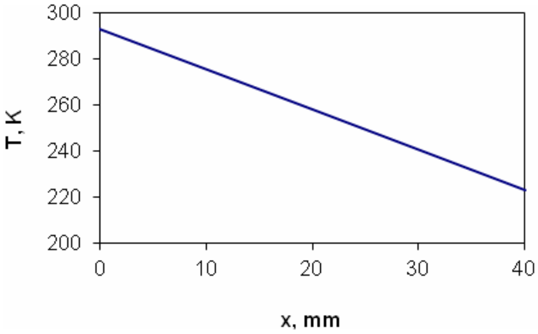


Figure 8-2

I.e. Eq. (8.5) can be rewritten as:

$$T(x) = T_a - \Delta T \frac{sh(px)}{sh(pL)} . \tag{8.8}$$

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

$$Q_{pas} = \kappa \frac{S}{L} \Delta T , \tag{8.9}$$

The exact calculation resulted from Eqs. (8.5), (8.6): 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 DX8020-100 Eq. (8.9). is applied for thermoresistors. For N wires Eq. (8.9). is written as:

$$Q_{pas} = N\kappa \frac{S}{L} \Delta T , \tag{8.10}$$

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, κ=400 W/mK, $\rho=1.667\cdot10^{-8}$ Ohm·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=20ºC. For an estimation of the passive heat load in the standard Q(ΔT) measuring option we take T_{cold}=-20 ºC.

The heat exchange for the wire surface is that of radiation. For copper we take the value of emissivity γ=0.02 (polished copper). Then the heat exchange coefficient equals α=0.095 W/(m^2·K).

For this instance the temperature distribution along the wire is non-linear - Figure 8-3.

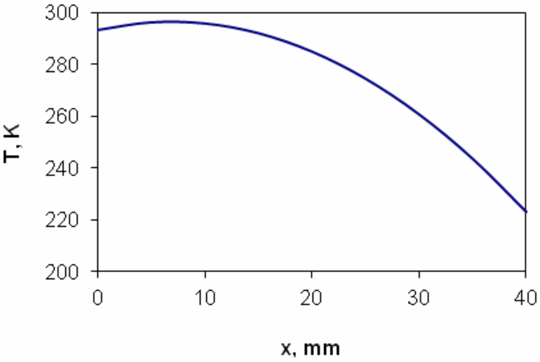


Figure 8-3

In the calculations the exact formulae (8.5-8.6) are necessary. As a result we have Q_{pas}=31 mW. The approximate Eq. (8.9), taking into account thermal conductance only would have been: Q_{pas}=12 mW, which is too rough an underestimation.

In the software DX8020-100 for the heater correction Eq. (8.6) is applied. For N wires Eq. (8.6) is written as follows:

$$Q_{pas} = NS\sqrt{A\kappa}\left[\frac{j^2\rho}{A}e^{pL} + \left\{\frac{j^2\rho}{A}\left(1-e^{pL}\right)+\Delta T\right\}\frac{ch(pL)}{sh(pL)}\right] \tag{8.11}$$

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.

9. *Mathematical 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:

$$y(x) = A_0 + A_1 x + A_2 x^2 + ... + A_{n-1} x^{n-1} + A_n x^n = \sum_{j=0}^{n} A_j x^j \tag{9.1}$$

Introducing the following coefficients:

$$\begin{gathered} a_{2n} = \sum_{i=1}^{N} x_i^{2n},\ a_{2n-1} = \sum_{i=1}^{N} x_i^{2n-1},\ \ldots,\ a_2 = \sum_{i=1}^{N} x_i^2,\ a_1 = \sum_{i=1}^{N} x_i,\ a_0 = N; \\ b_n = \sum_{i=1}^{N} y_i x_i^n,\ b_{n-1} = \sum_{i=1}^{N} y_i x_i^{n-1},\ \ldots,\ b_1 = \sum_{i=1}^{N} x_i y_i\quad b_0 = \sum_{i=1}^{N} y_i \end{gathered} \tag{9.2}$$

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

$$\begin{gathered} A_n \cdot a_{2n} + A_{n-1} \cdot a_{2n-1} + ... + A_1 \cdot a_{2n-n} + A_0 \cdot a_{n-1} - b_n = 0 \\ A_n \cdot a_{2n-1} + A_{n-1} \cdot a_{2n-2} + ... + A_1 \cdot a_{2n-1} + A_0 \cdot a_{n-2} - b_{n-1} = 0 \\ ... \\ A_n \cdot a_{n+1} + A_{n-1} \cdot a_n + ... + A_1 \cdot a_2 + A_0 \cdot a_1 - b_1 = 0 \\ A_n \cdot a_n + A_{n-1} \cdot a_{n-1} + ... + A_1 \cdot a_1 + A_0 \cdot a_0 - b_0 = 0 \end{gathered} \tag{9.3}$$

The mean square deviation is given by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} \left(P(x_i) - y_i\right)^2}{N}} \tag{9.4}$$

Let us consider an example of 2-power polynomial:

$$y(x) = Ax^2 + Bx + C, \tag{9.5}$$

If the following designations are true:

$$\begin{gathered} a = \sum_{i=1}^{N} x_i^4,\ b = \sum_{i=1}^{N} x_i^3,\ c = \sum_{i=1}^{N} x_i^2\quad d = \sum_{i=1}^{N} x_i,\ f = N, \\ aa = \sum_{i=1}^{N} y_i x_i^2,\ ab = \sum_{i=1}^{N} y_i x_i,\ ac = \sum_{i=1}^{N} y_i \end{gathered} \tag{9.6}$$

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

$$\begin{gathered} A \cdot a + B \cdot b + C \cdot c - aa = 0 \\ A \cdot b + B \cdot c + C \cdot d - ab = 0 \\ A \cdot c + B \cdot d + C \cdot N - ac = 0 \end{gathered} \tag{9.7}$$

For the linear interpolation:

$$y(x) = Ax + B \tag{9.8}$$

If we designate:

$$a = \sum_{i=1}^{N} x_i^2 \ , \ b = \sum_{i=1}^{N} x_i$$
$$aa = \sum_{i=1}^{N} y_i x_i \ , \quad ab = \sum_{i=1}^{N} y_i \qquad (9.9)$$

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

$$\begin{aligned} A \cdot a + B \cdot b - aa &= 0 \\ A \cdot b + B \cdot c - ab &= 0 \end{aligned} \qquad (9.10)$$

10. *Mathematical Annex VI*. Measurement of Imax, ΔTmax

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

$$\Delta T(I) = AI^2 + BI + C \qquad (10.1)$$

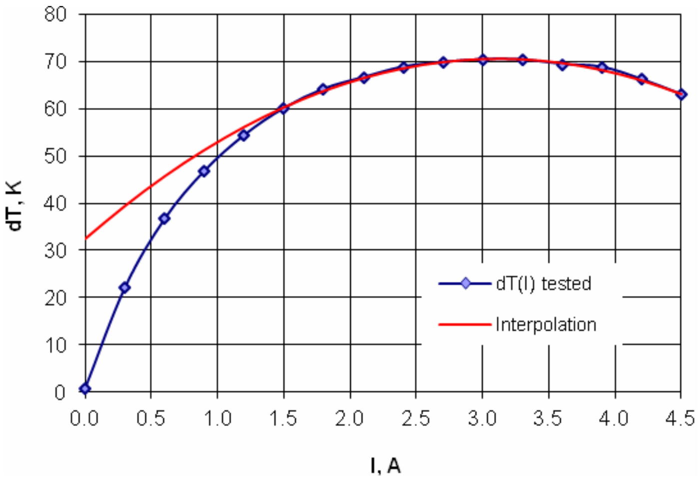
The interpolation is taken at the electric current segment [I_0, I_{lim}]. By default $I_0=0.5\cdot I_{max}$ is the starting measured point, $I_{lim}=1.2\cdot I_{max}$ is that finishing (I_{max} is the value taken from specifications or estimations).

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

$$I_{max} = -\frac{B}{2A}, \quad \Delta T_{max} = \Delta T(I_{max}) \qquad (10.2)$$

Let us take an example. Suppose the following data are measured (see Figure 10.1). The interpolating limits are taken as I_{lim}=4.5 A, I_0=1.5 A. The interpolation polynomial is given in Eq. (10.3) and is illustrated in Figure 10.1.

$$\Delta T(I) = -3.913\Delta T^2 + 24.417\Delta T + 32.554 \qquad (10.3)$$



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

The values are I_{max}=3.12A, ΔT_{max}=70.642K.

11. *Mathematical Annex VII.* Q_{max} Measurement and DT_{max} Correction

The measured points are linearly interpolated and the curve Q(ΔT) is obtained (see *Mathematical Annex V.* n-Power Polynomial Interpolation):

$$Q(\Delta T) = A \cdot \Delta T + B \qquad (11.1)$$

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

$$Q_{max} = B \qquad (11.2)$$

The value ΔT_{max} for the current I is obtained from Eq. (11.1) при $Q = 0$:

$$\Delta T_{max} = -\frac{B}{A} \qquad (11.3)$$

Consider an example. Suppose the measured data are given in Figure 11.1. 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 11.1.

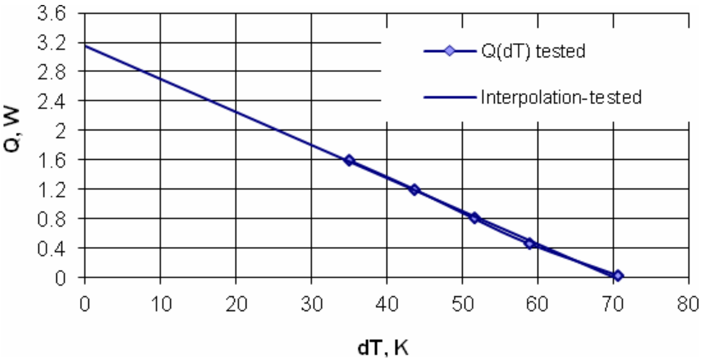


Figure 11.1

The mean square deviation in the range [35.9K, 68.7K]: σ=0.025 W.

Eq. (11.2) yields Q_{max}=2.929 W. With the help of Eq. (11.3) we obtain ΔT_{max}=71.35K.

If it is necessary to calculate corrections taking into account a passive heat flow Q_{pas} through the wires, for each point ΔT_i the passive heat load is estimated (see *Mathematical Annex IV.* Passive Heat Flux along the 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). An example of the corrected curves for the case illustrated by Figure 11.1 is given in Figure 11.2.

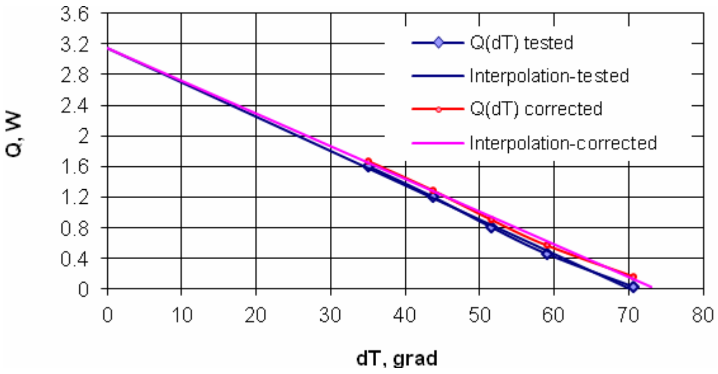


Figure 11.2

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

12. *Mathematical Annex VIII.* Measurement of TE Module Figure-of-Merit

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

$$\alpha I T_{cold} - \frac{1}{2} I^2 R - k'(T_{hot} - T_{cold}) = \frac{a_{cold}}{N}(T_a - T_{cold})$$
$$\alpha I T_{hot} + \frac{1}{2} I^2 R - k'(T_{hot} - T_{cold}) = \frac{a_{hot}}{N}(T_{hot} - T_a) \qquad (12.1)$$

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

Eqs. (12.1) 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

$$\frac{a_{cold}}{N} << k', \quad \frac{a_{hot}}{N} << k', \quad I << \frac{k'}{\alpha}. \qquad (12.2)$$

Accurate within the first order of smallness of the values (12.2), we find the following expression $Z = \alpha^2 \sigma / \kappa$:

$$Z = \frac{1}{T_a} \left[\frac{U_\alpha}{U_R}\right]_{av} \frac{(1 + b_{th})(1 + b_r)}{(1 + b_T)}. \qquad (12.3)$$

The ratio $\left[\frac{U_\alpha}{U_R}\right]_{av}$ in Eq. (12.3) 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:

$$b_{th} = B_{cond} + B_{rad}, \qquad (12.4)$$

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

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

$$b_r = \frac{2r}{R_{TEC}} \qquad (12.5)$$

where r is the electrical resistance of one wire, R_{TEC} is 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:

$$b_T = b_{T0} + b_{T1}(1 + b_{T0}) + b_{T2}, \quad b_{T0} = \frac{I^2 R N}{(a_{cold} + a_{hot}) T_a}, \qquad (12.6)$$

$$b_{T1} = -\frac{a_{cold}a_{hot}}{(a_{cold}+a_{hot})kN} + \frac{(\alpha I)^2 N}{(a_{cold}+a_{hot})k}, \quad b_{T2} = \left(\frac{a_{cold}-a_{hot}}{a_{cold}+a_{hot}}\right)^2 \frac{I^2R}{2kT_a}$$

The values a_{cold}, a_{hot} can be estimated considering natural convection in the air (if not in vacuum) and radiation: $a_{cold/hot} = (a_{conv} + a_{rad})S_{cold/hot}$, where a_{conv} and a_{rad} are convection and radiation heat exchange coefficients, respectively (see *Mathematical Appendices I, II*).

It is of vital concern that Eq. (12.3) remains true if the inequalities (12.2) are modified the following way:

$$\frac{a_{cold}}{N} << k', \quad a_{cold} << a_{hot}, \quad I << \frac{k'}{\alpha} \tag{12.7}$$

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-τ-metering option can be used for testing a TE module mounted on some header. Then $\frac{1}{a_{hot}}$ =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}:

$$Z = \frac{1}{T_{hot}}\left[\frac{U_\alpha}{U_R}\right]_{av} \frac{(1+b_{th})(1+b_r)}{1-\frac{a_{cold}}{kN}+\frac{I^2R}{2kT_{hot}}} \tag{12.8}$$

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

$$\Delta T_{max}(T_{a(hot)}) = T_{a(hot)} - \frac{\sqrt{1+2ZT_{a(hot)}}-1}{Z} \tag{12.9}$$

REFERENCE 1. Materials Useful Properties

In Table R1 some metals properties that may be used for reference are given.

Table R1

Material	**Density, kg/m^3**	**Thermal conductivity, W/mK**	**Specific heat, J/kgK**	**Electrical resistivity, 10^{-8} mOhm**
Aluminum	2700	237	900	2.8
Copper	8960	400	385	1.7
Gold	19320	317	128	2.3
Iron	7210	83	460	8.71
Lead	11210	35	130	19.3
Molybdenum	10220	138	249	5.6
Nickel	8910	90	448	6.1
Platinum	21450	72	133	10.9
Silver	10500	429	235	1.7
Stainless steel	8010	14.5	460	8.4
Tin	7310	64	226	10.1
Wolfram	19350	174	132	5.6
Zinc	7150	112	381	5.5

REFERENCE 2. Terms and Definitions

In Table R2 useful terms and definitions are given.

Table R2

Term	Definition if necessary	Symbol	Units
Ambient temperature		T_a	К
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 rejecting) surface	T_{hot}	K
Temperature difference	The difference of the values T_{hot} and T_{cold} for a TE module (TE module system)	ΔT	К
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	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 ambient, thermal radiation and conduction accompanying processes	Q_{pas}	W
TE module electric current		I	A
TE module electric voltage		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
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
TE module electric resistance	AC resistance of a TE module	R	Ohm
Figure-of-Merit	The combination of TE material parameters: the Seebeck coefficient a, electrical conductivity s and thermal conductivity k as $Z=\alpha^2\sigma/\kappa$. Characterizes the material efficiency at the temperature given.	Z	1/K

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