KD2 Pro

Thermal Properties Analyzer

Operator's Manual
Version 10
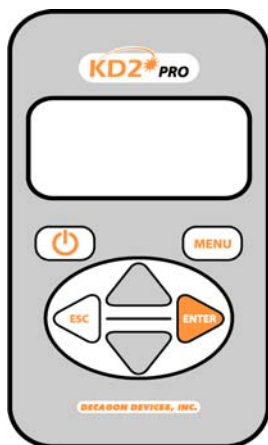
DECAGON DEVICES

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Contents

1. Introduction

Welcome to your new KD2 Pro Thermal Properties Analyzer. This guide is designed to help you understand and use your instrument to the best of its capability.

About the KD2 Pro

The KD2 Pro is a handheld device used to measure thermal properties. It consists of a handheld controller and sensors that can be inserted into the medium you wish to measure. The single-needle sensors measure thermal conductivity and resistivity; while the dual-needle sensor also measures volumetric specific heat capacity and diffusivity. Further details about the measurements and how they're made are given in chapters 2 and 3 of this guide.

Customer Support

If you ever need assistance with your KD2 Pro, or if you just have questions or feedback, there are several ways to contact us. Customer service representatives are available to speak with you Monday thru Friday, between 8am and 5pm Pacific time.

Phone:
1-800-755-2751 (Toll free to customers in US and Canada)
1-509-332-2756 (for international customers)

Fax:
1-509-332-5158

E-mail:
support@decagon.com or **sales@decagon.com**

If contacting us by email or fax, please include as part of your message your instrument's serial number, your name, address, phone, and fax number.

NOTE*: If you purchased your KD2 Pro through a distributor, please contact them for assistance.*

Warranty Information

The KD2 Pro has a 30-day satisfaction guarantee and a one-year warranty.

Seller's Liability

Seller warrants new equipment of its own manufacture against defective workmanship and materials for a period of one year from date of receipt of equipment (the results of ordinary wear and tear, neglect, misuse, accident and excessive deterioration due to corrosion from any cause are not to be considered a defect); but Seller's liability for defective parts shall in no event exceed the furnishing of replacement parts F.O.B. the factory where originally manufactured. Material and equipment covered hereby which is not manufactured by Seller shall be covered only by the warranty of its manufacturer. Seller shall not be liable to Buyer for loss, damage or injuries to persons (including death), or to property or things of whatsoever kind (including, but not without limitation, loss of anticipated profits), occasioned by or arising out of the installation, operation, use, misuse, non-use, repair, or replacement of said material and equipment, or out of the use of any method or process for which the same may be employed. The use of this equipment constitutes Buyer's acceptance of the terms set forth in this warranty. There are no understandings, representations, or warranties of any kind, express, implied, statutory or otherwise (including, but without limitation, the implied warranties of

merchantability and fitness for a particular purpose), not expressly set forth herein.

Repair Instructions

If your KD2 Pro should ever require a repair, call Decagon at **(509) 332-2756** or **1-800-755-2751** (United States and Canada). We will ask you for your address, phone number, your KD2 Pro's serial number, and your current firmware version. For non-warranty repairs, we will also ask for a method of payment.

Before shipping your instrument to Decagon, please contact Decagon to obtain a Request Maintenance Authorization Number (RMA). This will allow Decagon's repair staff to keep track of your KD2 Pro. Once you have acquired an RMA, send your KD2 Pro to Decagon. Please include a document listing the complete shipping address, name, and department of the person responsible for the instrument, <u>as well as a description of the problem</u>. This will better help our technicians and shipping department to expedite repair on your KD2 Pro, and ship it back to you.

Please pack your KD2 Pro carefully. Ship it back in the carrying case, preferably inside a cardboard box. Ship to:

Decagon Devices Inc.
2365 NE Hopkins Court
Pullman, WA 99163

Repair Costs

Manufacturer's defects and instruments under warranty will be repaired at no cost. For non-warranty repairs, costs for parts, labor, and shipping will be billed to you.

2. KD2 Pro Overview

The KD2 Pro is a battery-operated, menu-driven device that measures thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity. The KD2 Pro has been designed for ease of use and maximum functionality.

Specifications

Operating Environment:
Controller: 0 to 50 °C
Sensors: -50 to +150 °C

Power: 4 AA cells

Battery Life: At least 500 readings in constant use or 3 years with no use (battery drain in sleep mode < 50 uA)

Case Size: 15.5 cm x 9.5 cm x 3.5 cm

Display: 3 cm x 6 cm, 128 x 64 pixel graphics LCD

Keypad: 6 key, sealed membrane

Data Storage: 4095 measurements in flash memory (both raw and processed data are stored for download)

Interface: 9-pin serial

Read Modes: Manual and Auto Read

Sensors:

60 mm (small) single-needle (KS-1):
Size: 1.3 mm diameter x 60 mm long
Range: 0.02 to 2.00 W/(m · K) (thermal conductivity)
 50 to 5000 °C·cm/W (thermal resistivity)
Accuracy (Conductivity): ± 5% from 0.2 - 2 W/(m · K)
 ±0.01 W/(m · K) from 0.02 - 0.2 W/(m · K)
Cable length: 0.8 m

100 mm (large) single-needle (TR-1):
Size: 2.4 mm diameter x 100 mm long
Range: 0.10 to 4.00 W/(m · K) (thermal conductivity)
 25 to 1000 °C·cm/W (thermal resistivity)
Accuracy (Conductivity): ±10% from 0.2 - 4 W/(m · K)
 ±0.02 W/(m · K) from 0.1 - 0.2 W/(m · K)
Cable length: 0.8 m

30 mm dual-needle (SH-1):
Size: 1.3 mm diameter x 30 mm long, 6 mm spacing
Range: 0.02 to 2.00 W /(m · K) (thermal conductivity)
 50 to 5000 °C·cm/W (thermal resistivity)
 0.1 to 1 mm^2/s (diffusivity)
 0.5 to 4 mJ/(m^3K) (volumetric specific heat)
Accuracy: (Conductivity) ± 10% from 0.2 - 2 W/(m · K)
 ±0.01 W/(m · K) from 0.02 - 0.2 W/(m · K)
 (Diffusivity) ±10% at conductivities above
 0.1 W/(m · K)
 (Volumetric Specific Heat) ±10% at conductivi-
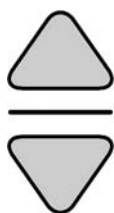 ties above 0.1 W/(m · K)
Cable length: 0.8 m

Keypad Operation
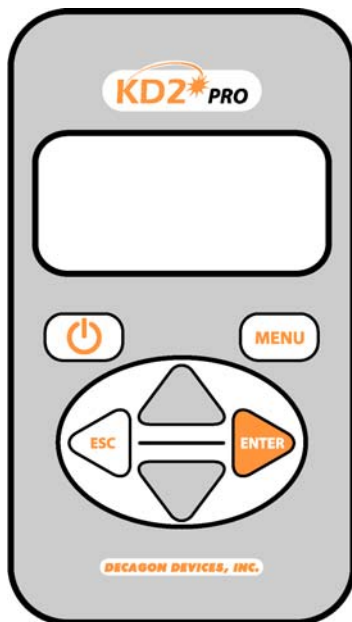
POWER: Located to the left below the screen, this key activates and deactivates the KD2 Pro. (Note: The device will automatically turn off if not used for more than 10 minutes, except while running in Auto Mode.)

MENU: Located to the right below the screen, this key cycles between the menus at the top of the screen.

ARROW KEYS: Located in the center of the keypad, these keys navigate within menus and sub-menus, and modify different settings in sub-menus. Holding down an arrow key allows you to scroll between different options quickly.

ESCAPE: This key backs out of sub-menus and can be used to cancel certain actions (see "Erase," in "Data Menu," Chapter 2).

ENTER: This key is used to make selections within menus and sub-menus, and also begins taking measurements (see "Making a Measurement," "Main Menu," below).

Choosing a Sensor

The KD2 Pro comes with three separate sensors, each of which is designed for measurements in specific sample types.

KS-1

The small (60 mm long, 1.3 mm diameter) single needle KS-1 sensor measures thermal conductivity and thermal resistivity. It is designed primarily for liquid samples and insulating materials (thermal conductivity < 0.1 W (W/m · K)). The KS-1 sensor applies a very small amount of heat to the needle which helps to prevent free convection in liquid samples (see Chapter 6 in this manual regarding measurement in liquid samples for more information). However, the small size of the needle and typically short heating time make the KS-1 a poor choice for granular samples such as soil and powders where contact resistance can be an important source of error. In insulating materials, the

errors from contact resistance become negligible making the KS-1 sensor a good choice.

TR-1

The large (100 mm long, 2.4 mm diameter) single needle TR-1 sensor measures thermal conductivity and thermal resistivity. It is designed primarily for soil, concrete, rock, and other granular or solid materials. The relatively large diameter and typically longer heating time of the TR-1 sensor minimize errors from contact resistance in granular samples or solid samples with pilot holes. The TR-1 needle heats the sample significantly more than the KS-1 sensor, which allows it to measure higher thermal conductivity samples (see specifications), but means that you **should not measure liquid samples with the TR-1 sensor**. The large diameter of the TR-1 is more robust than the KS-1, meaning that it is less likely to be damaged by normal usage conditions in soil or other solid materials. Additionally, the dimensions of the TR-1 sensor conform to the specifications for the Lab Probe called out by the IEEE 442-03 Guide for Soil Thermal Resistivity Measurements.

SH-1

The dual needle SH-1 sensor measures volumetric heat capacity, thermal diffusivity, thermal conductivity, and thermal resistivity. The SH-1 is compatible with most solid and granular materials, but **should not be used in liquids due to the large heat pulse** and possible resulting free convection in liquid samples.

Read Time

The read time is the time, in minutes, during which data are taken to compute thermal properties. Heat is applied for half of the time, and measurements are taken over the full time.

Thirty seconds are allowed for temperature equilibration before heating starts, so the entire time for a measurement is the time set here plus 30 seconds. Sixty temperature readings are taken during the read time, so the number entered here is also the number of seconds between temperature readings. This number is displayed in the upper right corner of the screen, and is available with each data record after downloading. Default read times are 1 minute for the KS-1 sensor, 2 minutes for the SH-1 sensor and 5 minutes for the TR-1 sensor.

The longer read time for the TR-1 sensor helps to prevent errors caused by effects of the large diameter needle and contact resistance between the sensor and the sample in granular and solid materials. If you wish to measure thermal properties of a sample with large grains or of a solid sample with a pilot hole that is significantly larger in diameter than the sensor, it is best to use the TR-1 needle and configure the read time to the maximum allowed 10 minutes.

The shorter read time for the KS-1 sensor reduces the amount of heat input into the sample. This is especially important with liquid samples where excessive sample heating can cause errors from free convection (see section on measuring liquid samples for more details). In low viscosity samples (e.g. water and aqueous solutions), the KS-1 read time should be configured to the minimum allowed 1 minute.

To set the read time, go to the Read Time menu selection and press Enter. Arrow down to the probe for which you want to set the read time and press Enter, Arrow up or down to the read time you want and press Enter.

KD2 Pro Sensor Compatibility

Sample Material	KS-1	TR-1	SH-1
Low viscosityliquids (e.g. water)	Best[1]	No	No
High viscosity liquids (e.g. glycerol, oil)	Best[2]	Ok[2]	No
Insulation and insulating materials	Best[3]	Ok	Ok
Moist soil	No	Best	Ok
Dry soil, powders, granular materials	No	Best[4]	Ok
Concrete	No	Best[5]	Ok[6]
Rock	No	Best[5]	Ok[6]
Other solids	No	Best[5]	Ok
Volumetric specific heat	No	No	Best
Thermal diffusivity	No	No	Best

[1] In low viscosity liquids, the read time should be set to the minimum allowed 1 minute and should only be used in low power mode to avoid free convection.

[2] In high viscosity liquids, the KS-1 or TR-1 sensor should only be used in low power mode.

[3] The KS-1 or TR-1 needles in low power mode with 10 min read time give good results with insulation. Heater temperatures with high power mode are quite high for insulation measurements.

[4] In dry granular materials where contact resistance can be significant, extending the read time to the maximum allowed 10 minutes will produce the most accurate results.

[5] In solid materials where a pilot hole has been drilled and contact resistance can be significant, using thermal grease and extending the read time to the maximum allowed 10 minutes will produce the most accurate results.

[6] The SH-1 sensor will take accurate measurements in rock and cured concrete, but it is very difficult to drill small diameter, parallel holes in these materials to accommodate the SH-1 needles.

Power Mode

With the KD2 Pro, you have the ability to configure the device to measure each of the three sensor types in either high power mode or low power mode. In high power mode, the KD2 Pro applies a relatively large heating current to the sensor during a measurement resulting in greater sensor heating. In low power mode, the KD2 Pro applies a small current to the sensor resulting in less heating of the sensor. The KS-1 sensor defaults to low power mode, while the TR-1 and SH-1 needles both default to high power mode. We recommend that the power mode only be changed from the default settings for special measurements by expert users. In all but a few cases, changing the power mode from the default settings will result in poorer accuracy than can be expected in the default power mode. Do not change the power mode from the default settings unless you are an expert user and are making a specialized measurement. Feel free to contact Decagon to discuss specifics of your measurement before changing from the default power mode setting. More specific comments regarding power mode adjustment include:

- Do NOT attempt to make measurements in liquids with the KS-1 or TR-1 in high power mode. The additional heating from the higher heat input will cause free convection and compromise the measurement (see Chapter 6 for more information on free convection).
- Do not attempt to make measurements in low viscosity fluids with the SH-1 (dual needle) sensor in either high power or low power mode.
- One motivation behind allowing power mode configuration is to allow the TR-1 and SH-1 sensors to make better measurements in frozen materials where the decreased heat input in low power mode is less likely to cause phase change (melting) of the frozen sample. One situation where we do recommend a non-default power mode setting is the measurement of thermal conductivity of snow. In this case, we recommend using the TR-1 needle to reduce issues with contact resistance, and we recommend configuring the sensor to low power mode to reduce issues with melting.

Installing the Sensors

The KD2 Pro's three sensors have been designed for ease of installation and use. The following considerations should be observed when installing the sensors.

- **The sensor should be inserted all the way** into the medium to be measured.
- For the single-needle 10cm sensor, a drill bit has been included that can be used to drill a pilot hole in material such as wood or hard soil. For rock (or cured concrete), a 1/8" hole can be drilled with a rotohammer and filled

with thermal grease to provide optimal contact between the needle and the rock.

- For the dual-needle sensor, **the needles must remain parallel to each other during insertion** to make an accurate reading. Therefore, take care in tough material, which can splay the prongs and adversely affect readings. Use the provided red tab with pilot holes to make sure that the needles have the correct spacing.

- Because the sensors give off a heat pulse, **you must allow a minimum of 1.5 cm of material** parallel to the sensor in all directions, or errors will occur.

- **DO NOT BEND THE NEEDLES**, as this can damage the sensor beyond repair. If the needle becomes bent, **do not bend it back**; contact Decagon for a replacement.

- **Good thermal contact between the sensors and the medium being measured is critical** for accurate measurements if a hole is drilled for sensor insertion. Make sure that the sensor fits tightly into the hole. Use the thermal grease included with your KD2 Pro to improve contact in larger holes or grainy samples.

Measurements In Concrete

If the KD2 Pro is to be used for measurements in concrete, it is preferrable to mold pilot holes in wet concrete using the pilot pins furnished with your KD2 Pro using the following procedure.

- Coat pilot pin with vaseline.
- Install pin at least 100mm deep while concrete is wet.
- Remove pin when concrete has dried.
- Coat the single 10cm sensor with thermal grease, insert sensor into the cast hole and begin to take readings.

If measurements need to be made in concrete that has already been cured, holes can be drilled into the sample using the procedure outlined above in the section titled "Installing the Sensors."

Measurements In Insulation

Insulation measurements are best made with the KS-1 probe using a 10 minute read time. The long read time minimizes contact resistance errors, and the low heat of the KS-1 needle reduces free convection errors. In foam insulation a hole should be drilled for the probe. Simply pushing in the needle can cause the insulation to bunch in front of the needle tip resulting in a poor fit and a consequently a faulty reading. In fiber type insulation materials, assure that the insulating materials are not unduly disturbed by the needle insertion. (i.e. pushed in front of the needle tip). Do not allow the probe to move during the measurement.

3. The Menus

The KD2 Pro features four main menus: MAIN, DATA, CONFIG, and AUTO (respectively). These menus access the KD2 Pro's features, and have been designed for ease of use. Here is a more detailed description of each menu.

The Main Menu

The Main Menu is responsible for taking measurements from whatever medium a sensor is inserted into.
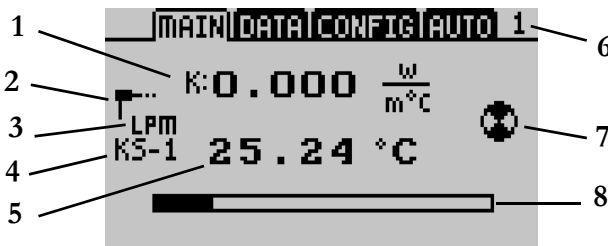
What you see:

1. The thermal property reading and the currently selected unit. The type of reading is indicated by the letter to the left of the reading:

   K = thermal conductivity

   C = specific heat capacity

   D = thermal diffusivity

   rho = thermal resistivity

   NOTE: When the spinner icon is visible, press the arrow keys to scroll through and change the current unit and measurement type.

2.   Icon showing connected sensor type.

3.   Indicator for high power mode (HPM) or low power mode (LPM).

4.   The currently connected sensor type and sensor name.

5.   The measurement temperature in °C or °F.

6.   Indicates the length of the reading in minutes

7.   Indicates the status of a reading.

8.   Progress bar that displays elapsed time.

The purpose of the Main Menu is to take measurements. The next section will explain how to do this.

Taking a Measurement

It is easy to take measurements with the KD2 Pro. Do the following to make a measurement:

NOTE: If the temperature of the sample is different from the temperature of the needle, the needle must equilibrate to the surrounding temperature before beginning a reading.

1.   Attach appropriate sensor then turn on the KD2 Pro.

2.   Properly insert the sensor into the material to be measured. (See "Installing the sensors" in this chapter for instructions.)

3. When the KD2 Pro turns on, you should be in the Main Menu. If not, press the Menu key until you arrive there. Press Enter to begin the measurement.

4. An icon will appear on the left and right side of the screen. The icon at left indicates the type of sensor connected. The circular icon indicates that a reading is underway. It will change to a thermometer icon to indicate whether the measurement is currently in heating or cooling mode; when the thermometer is rising, heat is applied to the needle, and when it is falling, heat is off. A progress bar shows the elapsed time.

5. When the progress bar has fully darkened, the results are displayed as follows:

```
┌─────────────────────────────┐
│ MAIN DATA CONFIG AUTO       │
│  0.122 W/mK    ◉ Save       │
│     34.0°C     ○ Annotate   │
│ err = 0.0016   ○ Discard    │
│     Record 2 of 4095        │
└─────────────────────────────┘
```

On the left side of the screen are three measured values:
- **Thermal Properties Reading -** The calculated thermal measurement.
- **Starting Temperature -** The initial tempera- ture prior to any heating or cooling.
- **Err Value-** The err value is the relative goodness of fit or relative error for the data set. It is a measure of how well the model fits the data (the Theory chapter of this manual describes the model that is fit to the data). If the model fits the data perfectly, then err = 0.0000. The pur-

pose of displaying this reading is to indicate possible problems with the data. A good data set will give err values below 0.0100, except at very low thermal conductivity (e.g. insulation materials). If the err value is unusually large, discard the data, wait fifteen minutes and take another reading.

On the right side of the screen are three save options:
• **Save -** You can save your reading as is;
• **Annotate -** You can attach a sample ID to your reading;
• **Discard -** Cancel the current reading and return to the main screen.

NOTE: If the data memory is full or the sample temperature was unstable during a reading, an error message is displayed at the bottom of the screen. If this should happen, you may still take readings <u>but you will be unable to save them to the KD2 Pro</u>.

How to annotate a reading: When you select the "Annotate" option, you will see a series of lines with an arrow above and below the first position. Use the up and down arrow keys to select a letter or number and press Enter to move to the next character (as shown below). If you have annotated a previous reading, the old annotation will remain to be modified or deleted.
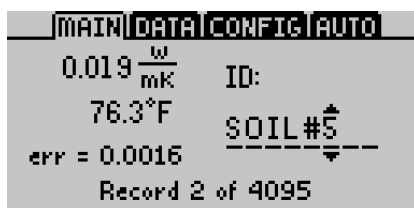
Repeat this until you reach the last character. When finished, simply continue to press Enter until you reach the end of the row. Holding Enter or Escape will allow you to scroll left and right through the Sample ID quickly.

NOTE: **It is important to wait for about fifteen minutes between readings, if the sensor is left in the same location!** If multiple measurements of a sample are made too rapidly in succession, the sample's temperature will not have had enough time to equilibrate from the previous reading, and the resulting measurement will be inaccurate. For best results, the sample should be as close to equilibrium as possible. A good environment for equilibration can be provided by placing the KD2 Pro sensor and sample in an isothermal chamber or styrofoam box.

The Data Menu

The Data Menu allows you to view stored data, download data to a computer, and erase the data from your KD2 Pro. It also displays how many readings have been recorded out of the total 4,095 that can be stored.

```
 MAIN DATA CONFIG AUTO
View
Download
Erase

    Recorded 12 of 4095
```

Here is description of each sub-menu:

VIEW: This menu allows you to view all data currently stored on your KD2 Pro. Press Enter to access the readings, and use

the arrow keys to scroll through them. By pressing Enter a second time, you can see more detail about a reading.

DOWNLOAD: This menu sends the data saved in the KD2 Pro to your computer. You have two download options:
- **Download All** - This downloads the temperature readings as well as the measured thermal properties.
- **Download Summary** - This downloads just the measured thermal properties.

<u>NOTE:</u> Your KD2 Pro comes with KD2 Pro Utility software for use with Microsoft Windows. The Utility makes downloading data to your computer very easy. In general, you should use the KD2 Pro Utility to download data instead of the download option on the KD2 Pro.

If you are unable to use the KD2 Pro Utility, you can use terminal software to transfer the data from your KD2 Pro to your computer. The following steps should apply to most terminal software programs:

1. Configure your terminal software with the following settings:
    - 9600 baud
    - 8 data bits, 1 stop bit, no parity
    - No software/hardware flow control
    - Append line feeds to incoming line ends
    - Echo typed characters locally.

2. Connect your KD2 Pro to an available serial port on your computer using the included RS-232 serial cable.

3. Set your terminal software to capture received data if you want to save the data.

4. Select the appropriate option from the Download menu in the KD2 Pro.

**ERASE:** This will erase all stored data on your KD2 Pro. **WARNING! This feature will completely erase all data on your KD2 Pro, and once activated, it cannot be undone!**

To erase data:
1. Press Enter to select the Erase sub-menu. The screen "Erase all stored data?" will appear.

2. Press Enter again to erase the memory or Escape if you decide not to continue. "Erasing..." will be displayed as data is being removed, which usually takes about 6 seconds.

3. When this is complete, you will be returned to the Data Menu.

The Configuration Menu

The Configuration Menu allows you to change system settings such as the date, time, measurement units, and also view information about your KD2 Pro. A battery icon will also display the remaining percentage of battery power. A description of each sub-menu follows.
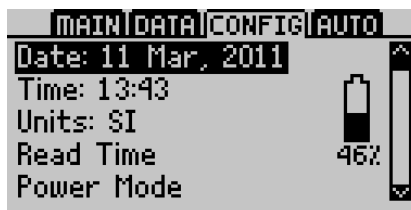
DATE: To change the current date,
1.   Press Enter to select the date display.

2.   The current date will appear in the center of the screen, in day/month/year format. A pair of arrows will be present above and below the first number.

3.   Use the up & down arrow keys to change this number.

4.   Press Enter to move to the next number, and repeat step #3. If you need to return to the previous number, press Escape.

5.   When you have finished changing the last number, press Enter and you will be returned to the Configuration Menu.

TIME: To change the current time,
1.   Press Enter to select the Time display.

2.   The current time will appear in the center of the screen, in 24-hour format. A pair of arrows will be present above and below the first number.

3.   Use the up & down arrow keys to change this number.

4. Press Enter to move to the next number, and repeat step #3. If you need to return to the previous number, press Escape.

5. When you have finished changing the last number, press Enter and you will be returned to the Configuration Menu.

UNITS: You can choose to represent measurement data in either SI or English units. Press Enter to select an option. When you return to the Main Menu, pressing the arrow keys allows you to scroll through and change the current unit and measurement type.
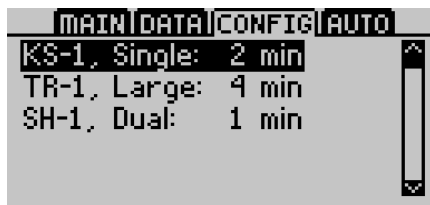
SI and English Unit Equivalents

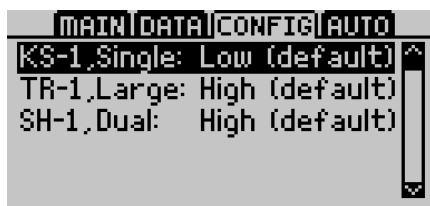|	Thermal Conductivity (K)	Thermal Resistivity (ρ)	Volumetric specific heat (C)	Thermal Diffusivity (D)
SI	$\dfrac{W}{(m \cdot K)}$	$\dfrac{°C \cdot cm}{W}$	$\dfrac{MJ}{(m^3 \cdot K)}$	$\dfrac{mm^2}{s}$
English	$\dfrac{BTU}{hr \cdot ft \, °F}$	$\dfrac{hr \cdot ft \, °F}{BTU}$	$\dfrac{BTU}{°F \cdot ft^3}$	$\dfrac{ft^2}{hr}$

NOTE: Readings in watts per meters-degree Celsius W/ (m °C) are the same as readings in watts per meters Kelvin (W/m· K), as Celsius and Kelvin degrees are on the same temperature scale.

READ TIME: Allows you to change the read time duration for each sensor type. To change a read time select the sensor and press enter. Using the up/down arrows to select the new read time. Press enter to save the changes or ESC to cancel

with out saving the changes. For more information refer to the read time section in chapter 2.

```
┌──────────────────────────────┐
│ MAIN DATA CONFIG AUTO        │
│ KS-1, Single:  2 min       ▲ │
│ TR-1, Large:   4 min         │
│ SH-1, Dual:    1 min         │
│                              │
│                            ▼ │
└──────────────────────────────┘
```

POWER MODE: Allows you to change the power mode to be used for each sensor type. **Do not change the power mode from the default settings unless you are an expert user and are making a specialized measurement.** To change the power mode, select the sensor and press enter to toggle between high and low power mode. Press ESC or MENU to accept the changes and exit the power mode menu. For more information on situations where you might want to change from the default power mode, see the Power Mode section in Chapter 2.

```
┌──────────────────────────────┐
│ MAIN DATA CONFIG AUTO        │
│ KS-1,Single: Low (default) ▲ │
│ TR-1,Large: High (default)   │
│ SH-1,Dual:  High (default)   │
│                              │
│                            ▼ │
└──────────────────────────────┘
```

CONTRAST: Allows you to change the screen contrast level. Press Enter and follow the on-screen instructions to modify the contrast.
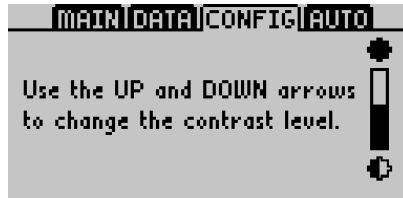
ABOUT: Displays the serial number and firmware version of your KD2 Pro.
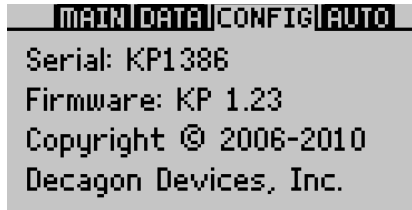
The Auto Mode

The Auto Mode allows you to set up the KD2 Pro to take readings automatically. You can select a measurement time in intervals of 15 minutes. The reading will be taken in the currently selected units from the Main Menu, and will begin as soon as you select this option. **NOTE:** Should the KD2 Pro's data memory ever become full (4,095 readings), you may still take readings, but you cannot save them until you erase the stored readings.
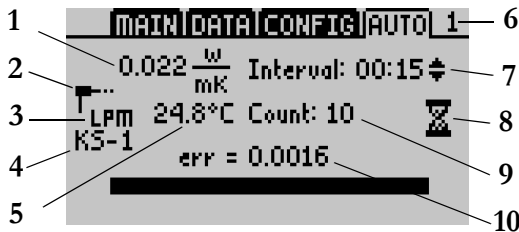
What you see:

1. Final measurement displayed in the selected units.

2. Icon showing connected sensor type.

3. Indicator for high power mode (HPM) or low power mode (LPM).

4. Currently connected sensor type.

5. Measurement temperature in °C or °F.

6. Indicates the length of the reading in minutes

7. Measurement interval. This time interval can be set either in the CONFIG menu or in the KD2 Pro Utility. **<u>NOTE:</u>** When the spinner icon is visible, press the arrow keys to change the interval time.

8. Hourglass icon indicating that time is elapsing until the next measurement.

9. Number of readings taken.

10. The err value of your data (see description of err value in the "Main Menu" section of this chapter for more details).

NOTE: The KD2 Pro Utility gives you more options to control how Auto Mode operates, including different time intervals, delayed start times, and others. Refer to the next chapter for more information.

4. The KD2 Pro Utility

KD2 Pro Utility main screen

The KD2 Pro Utility is a program designed specifically for interfacing with the KD2 Pro. Use this program to download measurement data to your computer, erase measurement data stored in the KD2 Pro, set the date and time, configure the KD2 Pro to take readings automatically, and see information about your KD2 Pro.

System Requirements

To use the KD2 Pro Utility, your computer must meet the following minimum system requirements:

- Microsoft Windows 98 or NT 4 (SP 5) or better
- Intel Pentium Pro or better processor
- One available serial port *or* one available USB port (most models of USB-to-serial adapters supported)
- Microsoft Excel 97 or better (for saving data as .xls files)

Installation

You can install the KD2 Pro Utility using the included CD-ROM (found in the inside cover of the KD2 Pro Operator's Manual). You can also download and install the latest version of the Utility on Decagon's download section of www.decagon.com.

Downloading Data
This will transfer all saved measurement data on the KD2 Pro to your computer. Do the following:

1. Make sure the RS-232 cable is connected to the KD2 Pro, and to a COM port on your computer.

2. Open the KD2 Pro Utility.

3. Choose the appropriate serial communication (COM) port from the "Use computer communication port" control on the main screen.

4. Click the "Download" button in the lower right-hand corner. You can also go to the File Menu, and select one of two options:
   1) Download Summary Data - Downloads and summarizes the data readings, but does not display per-second readings.
   2) Download All Data - Downloads all data currently stored in the KD2 Pro's memory. It displays complete data for

each measurement, including per-second readings.

If you encounter an error message after clicking this button, please refer to the Troubleshooting section for instructions.

Name your data file, select where it will be saved to, and in what format. You may choose between the fol-lowing formats:

• Microsoft Excel Workbook (*.xls);
• Comma delimited (*.csv);
• Tab delimited (*.txt);
• Raw data (also *.txt)

5. Click "Save" to download your data to the specified location. The progress bar shows the status of the download process:

KD2 Pro download dialog

NOTE: You can cancel a download in progress using the cancel button. If you cancel, no downloaded data are saved.

How Saved Data Are Organized

Measurement Data from the KD2 Pro is saved in the same basic format regardless of the file format chosen. You can choose to download just the summary data or all the measurement data which includes additional information. A description of each type of download follows.

Clicking the Download button or choosing "Download Summary Data" from the File Menu creates a file with the following columns:

- Measurement Time - Date and time when the reading was taken.
- Sensor - The model number of the sensor used for this reading.
- K (Thermal Conductivity) - as $W/(m \cdot k)$ or $BTU/(hr \cdot ft \cdot °F)$.
- rho (Thermal Resistivity) - as $°C \cdot cm/W$ or $hr \cdot ft \cdot °F/BTU$.
- C (Specific Heat) - as $MJ/(m^3 \cdot K)$ or $BTU/(°F \cdot ft^3)$. Columns for Specific Heat and Thermal Diffusivity are only included when the downloaded data contains measurements made with SH-1.
- D (Thermal Diffusivity) - as mm^2/s or ft^2/hr (dual-needle sensors only).
- Err- Quality of fit of the data to the KD2 Pro theoretical model.
- Temp(0) - Initial temperature of the sample as $°C$ or $°F$.
- Sample ID - If saved with the measurement.
- Read Time - as minutes from the start of heating. The interval between readings is also Read Time (in sec).

- Power Mode - Power mode selected during measurement.

Choosing "Download All Data" from the File Menu creates a file with all the data included in the summary file (listed above) and adds the following columns:

- Power - as W/m.
- Current - as amps.

The next 60 columns in the row hold the individual temperature reading the KD2 Pro uses to calculate the thermal properties of the sample. The data are shown as °C or °F.

Note that the time interval between the 60 individual temperature readings is scaled according to the read time selected. For instance, if a one minute read time has been selected, each of the 60 temperature readings are at 1 second intervals, while a 5 minute read time produces 60 temperature readings at 5 second intervals, etc.

The KD2 Pro Utility formats measurement dates according to the Windows Local settings found in the Control Panel under "Regional and Language Options" ("Regional Settings" in Windows 98). You can override this by going to the Preferences Menu > Data File tab, and selecting an option under "Date/Time Format". You can set this value to day/month/year format, using a 12- or 24-hour clock. (The Preferences Menu is explained in more detail later in this chapter.)

Erasing Your Data

This will erase all data stored on your KD2 Pro.
<u>WARNING!</u> Once this feature is activated, all data will

be permanently deleted from the KD2 Pro, and cannot be recovered!

To erase the data, do the following:

1. Make sure that the RS-232 cable is connected to the KD2 Pro, and to a COM port on your computer.

2. Choose the appropriate COM port from the "Use computer communications port" control on the main screen

3. Click "Erase," in the lower left-hand corner, or select "Erase Data..." from the File Menu.

   If you encounter an error message after clicking this button, please refer to the Troubleshooting section for instructions.

4. A progress bar shows the status of the erase process.

Setting the Date and Time

You can set the KD2 Pro's date and time by selecting "Set KD2 Pro Date/Time..." from the Actions Menu. This will automatically sync the KD2 Pro's date and time to your computer's time.

Setting the Auto Mode

The Auto mode of the KD2 Pro allows you to perform automated, unattended measurements at specified time intervals. The KD2 Pro has pre-set measurement intervals to select for this mode, but you can better customize how the KD2 Pro operates in Auto mode using the KD2 Pro Utility software. For example, you can select specific measurement intervals,

delayed start times, and the number of measurements from this menu.

To configure Auto Mode with the KD2 Pro Utility:

1. Connect your KD2 Pro to an available serial communication port on your computer. Select the name of your chosen serial port in the "Use computer communication port" control.

2. Choose "Configure Auto Mode..." from the Actions Menu. The following screen appears:
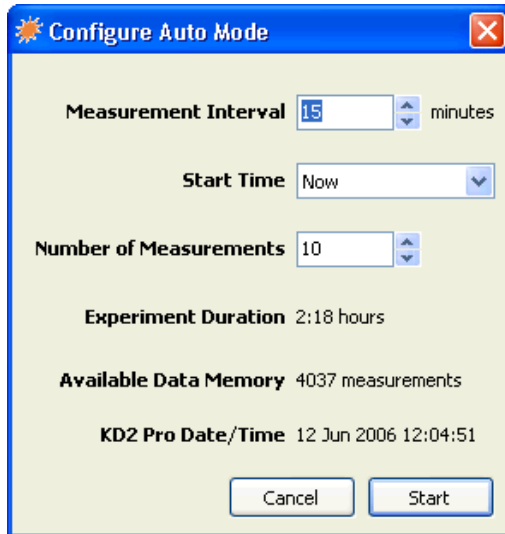
3. Choose values for Measurement Interval, Start Time, and Number of Measurements. Each of these values is explained below.

Measurement Interval

This is the time interval (in minutes) that you want the KD2 Pro to wait between measurements. The instrument must have a minimum of 15 minutes between measurements to allow for thermal gradients to dissipate. Therefore, you can select any number over 15 minutes, up to 1440 minutes (24 hours).

Start Time

You can select when you want the auto measurement to begin. You can choose start times ranging from "Start Now" to delaying the start for 24 hours. If you select "Start Now," you will have about 30 seconds to connect your thermal properties sensor to the KD2 Pro before the reading will start.

Number of Measurements

This is the total number of measurements that you want the KD2 Pro to make while in Auto Mode. The number is between 1 and the amount of available memory. As you change this value, the Experiment Duration value will change. The KD2 pro will store up to 4095 readings.

Experiment Duration

This is the total amount of time that your KD2 Pro will operate in Auto Mode, according to your measurement interval and number of measurements selected. This gives you an idea of how long the total Auto Mode experiment time will take.

Available Memory

This shows how much memory you have available for storing measurements. The KD2 Pro Utility prevents you from defining an experiment that could exceed the amount of available memory. If you reach the limit of memory storage, the KD2 Pro will stop taking measurements in Auto Mode.

KD2 Pro Date/Time

This shows the current time in your KD2 Pro. If the time is not correct, click the Cancel button, then choose "Set KD2 Pro Date/Time..." from the Actions Menu.

4. Click on the **Start** button. The KD2 Pro Utility will then send your settings to the KD2 Pro.

5. Unplug the serial cable from the KD2 Pro, then connect the desired thermal properties sensor to the instrument. Your KD2 Pro is now ready to make unattended measurements as you have programmed it.

Viewing KD2 Pro Information

Choose "View KD2 Pro Information..." from the Actions Menu to see information about your KD2 Pro:

KD2 Pro Information screen

This displays useful info about your KD2 Pro, including its serial number, firmware version and status, battery status, the number of currently stored measurements, and current data and time in the KD2 Pro's operating system.

The Menus and Their Functions

The KD2 Pro Utility features four main menus. These allow you to change program settings, as well as settings on the KD2 Pro. Below is a description of each menu and their functions.

File

Download Summary Data/Download All Data. Please see the "Download Data" section of this chapter for a description of these options.
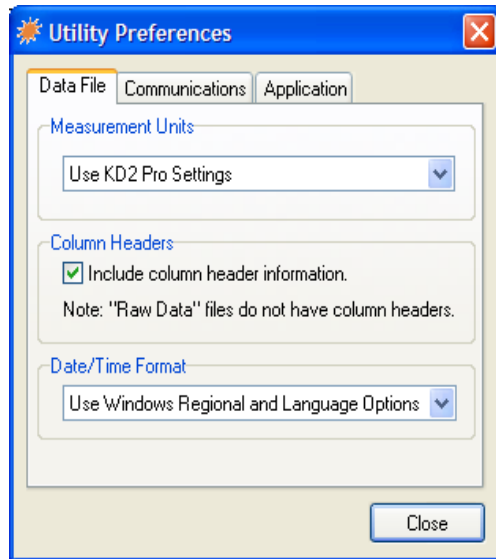
*Erase Data...*Erases all data in your KD2 Pro.

Edit

Preferences... This sub-menu modifies program settings, and settings for communicating with your KD2 Pro. It is divided into three sections called "tabs".

1. **Data File**

Preferences - Data File tab

Measurement Units: If you select "Use KD2 Pro Settings," this will save all downloaded measurement data in the units used on the KD2 Pro. You can also choose to override the settings in the KD2 Pro and save your measurement data using either SI (metric) or English units.

Column Headers: This option includes column headers (i.e. "Measurement Time," "Sample ID," etc.) for downloaded data.

Date/Time Format: Sets the date and time format for downloaded data files. See "How Saved Data are Organized" for more information.

2. **Communications**
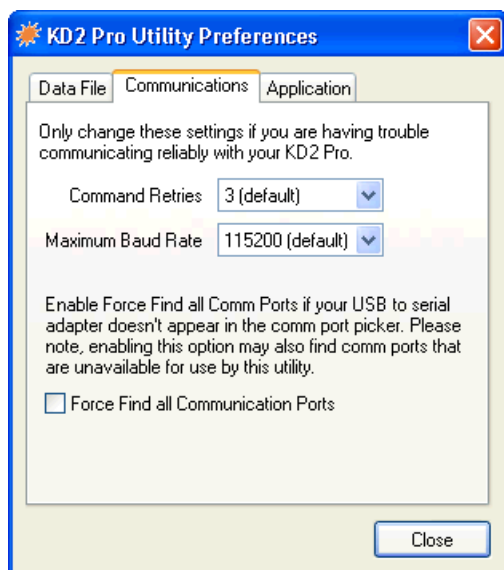
Preferences - Communications tab

Command Retries: If you encounter difficulty communicating with your KD2 Pro, you can set the number of times the computer should automatically try re-sending communications commands (up to 10).

Maximum Baud Rate: You can set the maximum baud rate for talking to your KD2 Pro. Choose a lower baud rate if you are not getting reliable communications from your device.

Force Find all Communications Ports: This will detect all COM ports on your computer, and should be used if your serial-to-USB adapter does not appear in the "Use computer communication port" control.

3. **Application**
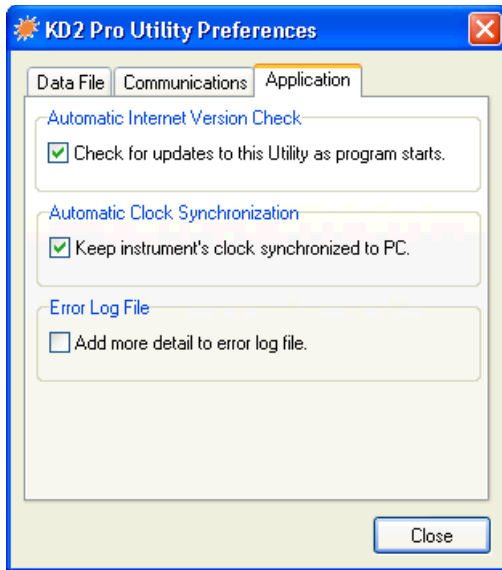
Preferences - Application tab

Automatic Internet Version Checks: If you select this option, the KD2 Pro Utility will automatically check for a newer version using Decagon's internet version check engine. It will notify you when a newer version is available when your computer is connected to the internet. You can turn off the automatic check by un-checking this option. You can manually check for updates anytime using the "Check for Utility Updates..." option in the Help Menu.

Automatic Clock Synchronization: Automatically sets the KD2 Pro's time to your computer's time, when you are connected to it. (See instructions above for setting this manually.)

Error Log File: This adds more troubleshooting messages to the error log, which can be sent to Decagon.

Actions

Set KD2 Pro Date/Time... See "Setting Date and Time" section earlier in this chapter for more information.

Set Auto Mode. Allows you customize how the KD2 Pro operates in Auto mode using the KD2 Pro Utility software. You can program specific time intervals and start times in this menu. See "Setting the Auto Mode" section earlier in this chapter for more information.

View KD2 Pro Information... Displays information about your KD2 Pro. See "Viewing KD2 Pro Information" section earlier in this chapter for more information.

Help

Help. Accesses the KD2 Pro Utility help file, which provides detailed information on how to use the program.

Send Feedback to Decagon

This menu item helps you send product feedback, bug reports, or feature requests to Decagon. Your computer must be connected to the internet for this feature to work. See Appendix B for more information.

Check for Utility Updates... If you select this function when connected to the internet, the KD2 Pro Utility will check for a newer version using Decagon's internet version check engine. It will notify you if a newer version is available.

Check for Firmware Updates... If you select this function when connected to the internet, the KD2 Pro Utility will check for updates for the KD2 Pro's operating system (firmware).

About KD2 Pro Utility... Displays the current program version and Decagon contact information.

Troubleshooting

The following descriptions should help you if you encounter any difficulty using the KD2 Pro Utility.

PROBLEM: The KD2 Pro Utility tells me the communication port I want to use is in use by another application, but I don't think any other programs are running.

SOLUTION: Some PDA synchronization software monitor serial communication ports. Disable Microsoft's ActiveSync or Palm's HotSync system software while using the serial port with the KD2 Pro Utility.

PROBLEM: My USB to Serial adapter is not showing in the communication port picker.

SOLUTION: Enable "Force find all Communication Ports" in Preferences by going to the Edit > Preferences, and to the Communication tab. Enable the check box at the bottom of the screen. Enabling this option may find other serial ports that are not available for use by the KD2 Pro Utility (for example, modems installed in your computer).

PROBLEM: Downloading data stops in the middle with an error message saying the Utility lost connection with the KD2 Pro.

SOLUTION: A noisy serial connection can disrupt the connection between the Utility and the KD2 Pro. If this error happens regularly, you can try setting your baud rate lower or increasing the number of times a command is sent to the KD2 Pro. Choose the "Communications" tab in Preferences to alter this.

5. Good Practices

The quality of the measurements you get with the KD2 Pro can be strongly affected by your experimental technique. The following suggestions will help you to recognize and avoid pitfalls in data collection so that the data you obtain can be as accurate as possible.

1. **Keep the temperature of the sample as constant as possible during the measurement.** The measurement is made by heating a needle that is placed in the sample and monitoring either the temperature of that needle or a second needle adjacent to the heater. The heat input is made as small as possible to avoid thermally driven redistribution of moisture in the sample. The temperature change from heating may therefore be only a few tenths of a degree. Sample temperature changes during the measurement period degrade the data and make it difficult for the inverse calculation to find the correct values for the thermal properties. The algorithms in the KD2 Pro are several orders of magnitude less sensitive to these errors than the conventional approach (plotting temperature vs. log time during heating and looking for a linear portion of the graph) but there can still be errors if the temperature changes too rapidly during a measurement. To minimize these sources of error:

    a. <u>In the laboratory, allow samples and sensors to come to temperature equilibrium</u> before the measurement starts. Fifteen to twenty minutes is a reasonable rule of thumb.

b. <u>Allow time between readings for temperatures to re-equilibrate.</u> Fifteen minutes between readings isn't too much.

c. <u>If measurements are made in an oven or a freezer, make sure the sample temperature is relatively constant before the measurement starts.</u> Measurements made on a sample taken from an oven and cooling to room temperature can show significant errors if the cool rate is too fast.

d. <u>When measuring thermal properties in the field, allow a minute or so after sensor insertion for temperature equilibration.</u>

2. **Minimize contact resistance.** In granular materials, or in solids where a hole has been drilled to accommodate the sensor, there is an additional thermal resistance between the heated sensor and the material into which the sensor is inserted. This extra resistance is called a contact resistance, and it decreases the thermal conductivity value registered by the sensor. This effect can be minimized by applying thermal grease to the sensor prior to inserting it as described in the Decagon Application Note "Reducing Contact Resistance Errors in KD2 Thermal Properties Measurements" located in the literature section of www.decagon.com/thermal. When a hole is drilled for the sensor, make sure the fit of the sensor in the hole is as tight as possible. Thermal grease can be injected into the hole to improve contact.

Long read times also decrease the effect of contact resistance. If you are measuring a sample that might give errors from contact resistance, increase the read time from the default to the maximum (10 minutes) for most accurate results. Finally,

dry granular materials and powders have large contact resistance. Always use the TR-1 or SH-1 sensor in these types of materials.

Avoid convection in liquid samples. See the next chapter for a more detailed explanation about this.

3. **Don't bend the needles.** Needle spacing on the dual needle sensor is critical for accurate measurements. A 1% change in needle spacing results in a 2% error in measurement of diffusivity and specific heat. A guide is provided for maintaining proper needle spacing during insertion of the sensor into a sample. The Delrin verification block included with your system shows the correct sensor spacing. If a needle is slightly bent, it can be carefully straightened until the tip spacing matches the hole spacing in the calibration block.

6. **Measuring Liquids**

The KD2 Pro KS-1 sensor is specifically designed to measure thermal conductivity/resistivity of liquid samples. However, measuring thermal properties of liquids is difficult, and great care must be taken for accurate and repeatable results. For an accurate measurement of thermal properties of a liquid sample, the sample must be absolutely still in relation to the KS-1 sensor. Convection, or bulk movement of the sample, will result in error in the thermal properties measurement. Error from convective heat exchange is often very large, rendering the thermal properties measurement useless, and must be avoided. Please note that the **TR-1 and SH-1 sensors are not designed for thermal properties measurement in liquids**, and will not give accurate results in those materials.

Convective heat exchange in fluids can be broken down into two categories: forced and free convection. Forced convection occurs when the fluid is agitated or mixed by mechanical forces. Free convection may occur when a body of higher or lower temperature is inserted into a fluid. The temperature difference between the body and fluid creates density gradients in the fluid, and these density gradients cause the fluid to mix. From a practical standpoint certain steps can be taken to minimize both forced and free convective heat exchange.

To eliminate forced convection, the fluid sample and the sensor must be absolutely still during the measurement. Even minute vibrations in the sample are often enough to compromise the thermal properties measurement. Some common

sources of vibrations found in the laboratory that have been shown to affect thermal properties measurement in liquids and must be avoided include:

- Vibration from HVAC (Heating, Ventilating, and Air Conditioning) systems
- Vibration from computer fans that are near the measurement apparatus
- Vibration from people moving around the lab
- Vibration from other laboratory equipment

If sources of vibration are present in laboratory, it may be necessary to place the sample on a vibration isolation table to prevent errors from convection. Another common strategy is to configure the KD2 Pro in auto mode and make measurements overnight after turning off the HVAC system and any other lab equipment that might cause vibrations.

The KD2 Pro KS-1 sensor is specially designed to add a very small amount of heat to the sample during measurement and thereby minimize problems with free convection. In high viscosity liquids (e.g. oils, glycerin), free convection is generally not an issue. However, in low viscosity liquids like water or aqueous solutions, there are several important steps that will aid in accurate measurements.

- When dealing with low viscosity liquid samples, the duration of the read time should be minimized to minimize the amount of heat added to the sample.
- The default read time for the KS-1 sensor is 1 minute. If you are measuring in low viscosity liquids, use this read time.

- In liquid samples, the KS-1 sensor needle should be oriented vertically during the measurement to help prevent free convection.
- Never use the KS-1 sensor in high power mode in liquids. The sensor must be configured in low power mode to prevent free convection.

Liquid Sample Temperature Control

Often it is desirable to control the temperature of the liquid sample above or below ambient temperature during thermal properties measurement. It is important that the act of heating or cooling the sample doesn't cause forced or free convection as mentioned above. There are several things that should be avoided when measuring thermal properties of heated or cooled samples.

- Do not heat the sample from the bottom (e.g. on a hot plate). The temperature gradient from the heating will cause free convection.
- Do not make measurements in a conventional refrigerator or freezer. Conventional cooling devices have very large cyclical temperature cycles which can cause excessive sample temperature drift and poor measurements. Vibrations from the compressor will also cause forced convection in the sample.
- Do not measure the thermal properties of the sample while it is in a circulating water bath. The vibrations from the water bath pump and from the circulating water will cause forced convection in the sample.

According to several researchers who use the KD2 Pro with liquid samples, the best method for controlling temperature of liquid samples is as follows.

1. Heat or cool the sample (with sensor inserted) in a water bath.

2. Once the sample temperature has equilibrated to the desired water bath temperature, turn the water bath off.

3. Allow enough time for the water bath to become absolutely still, and make the measurement.

NOTE: Experimental results from researchers have shown that the KD2-Pro KS-1 sensor can make accurate measurements in water and aqueous solutions up to about 50 C. Above this temperature, the viscosity of the water becomes too low and free convection begins to affect the measurement.

For a more in-depth discussion of measuring thermal properties of liquids, download the application note or watch the video on this subject from www.decagon.com.

7. Care and Maintenance

Although the KD2 Pro has been built to high construction standards, proper care must be taken to ensure continuing operation.

Cleaning & Caring for the Sensors

The sensors are easy to clean. The sensor needles are stainless steel, and as such, when they need cleaning, wipe them with a damp cloth. Take care never to bend the needles. If the sensor becomes badly bent, *do not attempt to bend it back*; this may break it. You will need to contact Decagon to obtain a replacement sensor.

Changing the Batteries

Although the KD2 Pro has been designed to provide an excellent battery lifespan, the batteries will eventually require changing. When this happens, a low-battery indicator will appear in the upper left hand corner of the screen. The KD2 Pro requires four alkaline "AA" batteries. To change the batteries:

1. Turn over the KD2 Pro and locate the battery cover.

2. Place your thumb on the grooves and push upward to loosen the cover.

3. Remove the old batteries and insert new ones. Be sure to orient the fresh batteries according to the polarity marks shown in the case.

4. Update the time and date either in the Configuration Menu of the KD2 Pro, or by using the KD2 Pro Utility.

Troubleshooting

If you encounter problems with your KD2 Pro, refer to the following items to see if they resolve your problem.

PROBLEM: I am getting poor or inconsistent readings.

SOLUTION: Review section 5 of this manual.

PROBLEM: The KD2 Pro says it does not recognize the connected sensor.

SOLUTION: Make sure the connection between the sensor and the KD2 Pro is secure, and that none of the connector pins are bent or broken off. If the KD2 Pro still fails to recognize the sensor, the sensor may be malfunctioning. Contact Decagon for more assistance.

Verifying Sensor Performance

With your KD2 Pro, you have received three standard materials with which you can verify that your KD2 Pro is working correctly and maintaining accuracy: a clear vial of glycerin (glycerol) for the KS-1 Sensor, a white plastic cylinder for the SH-1 needle sensor and a black plastic cylinder for the TR-1 single needle sensor.

The glycerol should be used to verify performance of the KS-1 sensor. The cap of the vial is equipped with a septum allowing direct insertion of the needle into the vial through the cap.

Note: After repeated use the septum may begin to leak. Replacement septums have been provided with your instrument. To replace simply remove the cap, press the old septum out and press new one back in.

To conduct a performance verification, insert the needle fully into the glycerol. The needle should be oriented vertically, and it is best to turn the vial of glycerol upside-down on top of the needle, so that any bubbles in the glycerol float to the top away from the needle. The needle should be approximately centered in the vial, and must not be touching a side of the vial. Before taking a measurement in the glycerol, make sure that the system is not undergoing rapid temperature drift. Even the heat from holding the vial in your hand for a few seconds, or the cooling from direct air conditioning flow can decrease the accuracy of the measurement. It is best to place the needle and vial in an isothermal environment (e.g. insulated chamber or cooler), and allow 15 minutes of equilibration time before taking the measurement. The thermal conductivity of the glycerol is $0.285 \text{ W}/(\text{m} \cdot \text{K})$ at 20 °C.

The two-hole Delrin block should be used to verify the performance of the dual-needle (SH-1) sensor. The sensor should be fully inserted into the pre-drilled holes in the Delrin, and allowed to equilibrate for at least 15 minutes before taking the measurement. Again, make sure that the system is not undergoing rapid temperature drift. Even the heat from holding the block in your hand for a few seconds, or the cooling from direct air conditioning flow can decrease the accuracy of the measurement. It is best to place the needle and block in an isothermal environment (e.g. insulated chamber or cooler), and allow 15 minutes of equilibration time before taking the measurement. The Delrin blocks have slightly different thermal conductivities from lot to lot, so the correct values for K,

C, and D for your individual Delrin block are recorded on your Certificate of Quality Assurance.

Verification for the TR-1 is similar to that for the SH-1. Place the needle in the block and take a reading, taking care to minimize temperature distrubances. The reading should correspond to the value recorded on your Certificate of Quality Assurance.

At the request of multiple KD2 Pro users, we have characterized the temperature dependence of the thermal conductivity of the black plastic TR-1 verification cylinder. Measurements were collected on three black plastic cylinders from different lots of material over the temperature range of -20 to 60 C (see figure below). We found little temperature dependence on any of the samples with maximum differences over the -20 to 60 C range never being greater than 0.004 W m-1 K-1 (~1%).
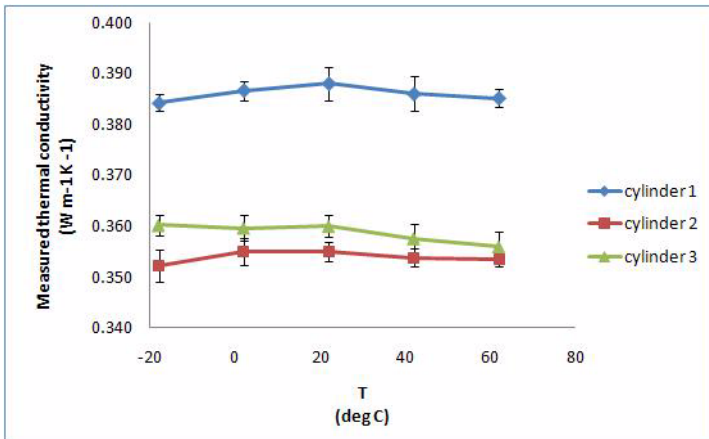
Thermal conductivity as a function of temperature for three TR-1 verification cylinders from different lots of material. Error bars represent ±1 standard deviation in five replicated measurements.

8. KD2 Pro Theory

Transient line heat source methods have been used for over 50 years to measure thermal conductivity of porous materials. Typically a probe for this measurement consists of a needle with a heater and temperature sensor inside. A current is passed through the heater and the temperature of the probe is monitored over time. An analysis of the probe temperature is used to determine thermal conductivity. More recently the heater and temperature sensor have been placed in separate needles. In the dual probe the analysis of the temperature vs time relationship for the separated probes yields information on diffusivity and heat capacity as well as conductivity.

An ideal sensor would have a very small diameter, and a length perhaps 100 times its diameter. It would be in intimate contact with the surrounding material and would measure the temperature of the material during heating and cooling. Ideally the temperature and composition of the material being measured would not change during the measurement.

Real sensors fall short of the ideal in several ways. A probe small enough to be ideal would be too fragile for most applications. Measurements in outdoor environments involve changing temperatures; the ambient temperature generally is not constant. Heating moist, unsaturated soil causes water to move away from the heat source, thus altering the water content in the region of measurement, and the hole made for the probe often disturbs the material around it causing a contact resistance between the probe and the material.

It is a challenge to design a probe that gives accurate measurements under all conditions. If the probe is too small it is fragile, and the contact resistance can be high in dry, porous

materials. A long heating time is required for a large probe, but the long heating time drives water away from the probe and can cause free convection in liquid samples, thus altering the reading. A high heating rate makes temperature changes easier to read and less susceptible to temperature drift errors, but results in water movement out of the measuring region and free convection in liquids. Long heating times are also recommended to minimize contact resistance, but, again, result in water movement away from the probe.

Decagon's KD2 Pro design attempts to optimize thermal properties measurements relative to these issues. Probes are relatively large and robust making them easy to use. Heating times are kept as short as possible to minimize thermally induced water movement and minimize time required for a measurement. Heat input is minimized to minimize water movement and free convection. Use of relatively short heating times and low heating rates requires high resolution temperature measurements and special algorithms to measure thermal properties. The KD2 Pro resolves 0.001 C in temperature. It uses special algorithms to analyze measurements made during a heating and a cooling interval. It also uses special algorithms to separate out the effects of the heat pulse from ambient temperature changes. Two different algorithms are used, one for the dual needle probe and one for the single needle. Both are based on the line heat source analysis given in Carslaw and Jaeger (1959) and Kluitenberg et al. (1993).

Dual Needle Algorithm

Heat is applied to the heated needle for a set heating time, t_h, and temperature is measured in the monitoring needle, 6 mm distant during heating and during the cooling period following heating. The readings are then processed by subtracting the ambient temperature at time 0, multiplying by 4π and dividing

by the heat per unit length, q. The resulting data are fit to the following equations using a non-linear least squares procedure.

$$T^* = b_0 t + b_1 \left\{ Ei\left(\frac{b_2}{t}\right) - Ei\left[\frac{b_2}{(t - t_h)}\right] \right\}$$

$$T^* = b_0 t + b_1 Ei\left(\frac{b_2}{t}\right)$$

(1)

where:

$$T^* = \frac{4\pi(T - T_o)}{q}$$

(2)

Here, Ei is the exponential integral (Abramowitz and Stegun, 1972), and b_o, b_1 and b_2 are the constants to be fit. T_o is the temperature at the start of the measurement and q is the heat input. The first equation applies for the first t_h seconds, while the heat is on. The second equation applies when the heat is off. The thermal conductivity is computed from

$$k = \frac{1}{b_1}$$

(3)

The diffusivity is

$$D = \frac{r^2}{4b_2}$$

(4)

The conductivity and diffusivity are found by fitting eqs. 1 to the transformed data. The correct values of b_0, b_1 and b_2 are the ones which minimize the sum of squares of error between the equations and the measurements. The values are found using the Marquardt (1963) non-linear least squares procedure. This procedure is susceptible to getting stuck in local minima and failing to find a global minimum in some problems (the single needle problem is a perfect example of a bad non-linear least squares problem) but the dual needle problem typically works well. Finding just three model parameters is quick in the KD2 Pro.

Single Needle Algorithm

Heat is applied to a single needle for a time, t_h, and temperature is monitored in that needle during heating and for an additional time equal to t_h after heating. Two needle sizes are used. One (the KS-1) is 1.2 mm diameter and 60 mm long. The other (the TR-1) is 2.4 mm diameter and 100 mm long. The temperature during heating is computed from

$$T = m_0 + m_2 t + m_3 \ln t$$

(5)

m_0 is the ambient temperature during heating (which could include some offset for contact resistance and the heating element being adjacent to the temperature sensor inside the needle), m_2 is the rate of background temperature drift, and m_3 is the slope of a line relating temperature rise to logarithm of temperature.

During cooling the model is

$$T = m_1 + m_2 t + m_3 \ln\left[\frac{t}{(t - t_h)}\right]$$

(6)

The thermal conductivity is computed from

$$k = \frac{q}{4\pi m_3}$$

(7)

Since these equations are long-time approximations to the exponential integral equations (eq. 1), we use only the final 2/3 of the data collected (ignore early-time data) during heating and cooling. This approach has several advantages. One is that effects of contact resistance appear mainly in these early-time data, so by analyzing only the later time data the measurement better represents the thermal conductivity of the sample of interest. Another advantage is that equations 5 and 6 can be solved by linear least squares, giving a solid and definite result. The same data, subjected to a non-linear least squares analysis,

can give a wide range of results depending on the starting point of the iteration because the single needle problem is susceptible to getting stuck in local minima. The linear least squares computation is also very fast.

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Further Reading

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Please visit **www.decagon.com** for more information on thermal properties in relation to density, water content, and temperature.

Appendix A

Table of Thermal Units

	Column 1: SI Unit	To convert Column 1 into Column 2, multiply by:	Column 2: English Unit	To convert Column 2 into Column 1, multiply by:
heat	Joule	0.000952	BTU	1054
heat	Joule	0.239	cal	4.186
heat flux density	W/m^2	0.00143	$cal/(cm^2\ min)$	698
thermal conductivity	$W/(m \cdot K)$	0.578	$BTU/(hr \cdot ft\ °F)$	1.73
thermal conductivity	$W/(m \cdot K)$	6.93	$BTU \cdot in/(hr \cdot ft^2\ °F)$	0.144
thermal resistivity	$cm \cdot °C/W$	0.0173	$ft \cdot hr\ °F/BTU$	57.8
thermal resistivity	$cm \cdot °C/W$	.00144	$ft^2\ hr \cdot °F/(BTU \cdot in)$	693
specific heat	$J/(kg \cdot K)$	2.39×10^{-4}	$BTU/(lb \cdot °F)$	4179
diffusivity	mm^2/s	0.0388	ft^2/hr	25.794
diffusivity	m^2/s	.1076	ft^2/s	9.29

Appendix B

Send Feedback to Decagon

Decagon Software makes it easy to send feedback, bug reports, and feature requests to Decagon or your Decagon Distributor. Choose "Send Feedback to Decagon..." from the help menu. This opens the window shown below.

Enter your name, company name, and other contact information. Tell us what type of feedback you are sending (General Feedback, Feature Suggestions, Bug Report, or Other). Indicate how you want us to respond to your feedback (E-mail or Telephone).

Use the description area to give details for your feedback. If you are reporting a bug, it is very helpful for you to tell us what steps you took for the bug to happen and any error message you saw. By default, bug reports also include the software error files.

You can send Decagon a file using this form too. This is useful for sending data files that you have questions about.

If you work directly with a Decagon representative, put their E-mail address in the field at the bottom of the form. This sends the contents of the form to them. Your Decagon representative can follow-up with you directly.

KD2 Pro CE Compliance

DECLARATION OF CONFORMITY

Application of Council Direction: 89/336/EEC

Standards to Which Conformity is   EN55022: 1987
Declared: EN500082-1: 1991

Manufacturer's Name: Decagon Devices, Inc.
2365 NE Hopkins Ct.
Pullman, Washington 99163
USA

Type of Equipment: Thermal Properties Meter

Model Number: KD2 Pro

Year of First Manufacture: 2006

This is to certify that the KD2 Pro Thermal Properties Meter, manufactured by Decagon Devices, Inc., a corporation based in Pullman, WA, USA meets or exceeds the standards for CE compliance as per the Council Directives noted above. All instruments are built at the factory at Decagon and pertinent testing documentation is freely available for verification.

Index

A

B

C