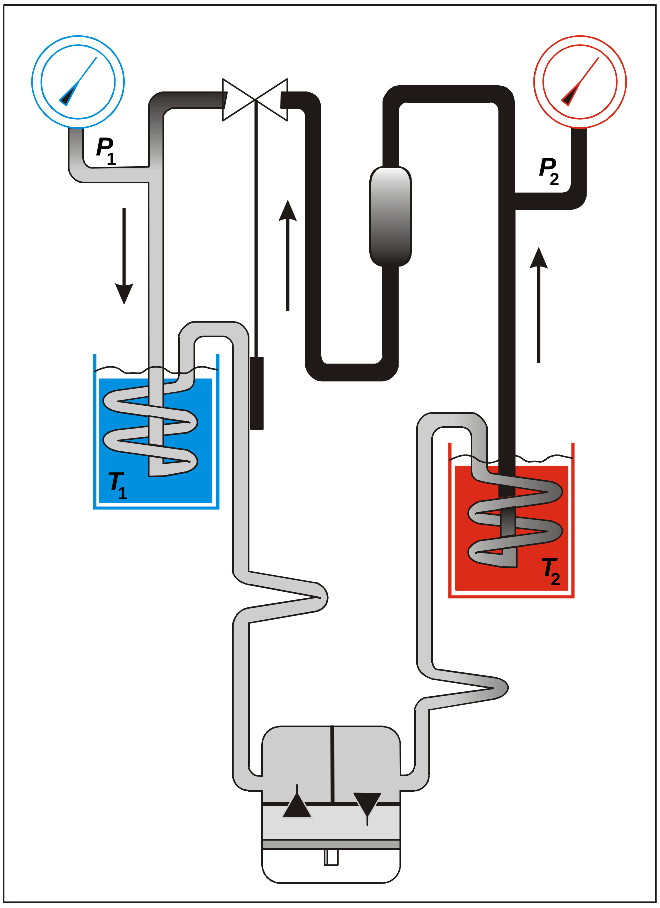
Determining the efficiency of the heat pump as a function of the temperature differential

Objects of the experiment

- Understanding of the principle of the heat pump.
- Determination of the efficiency of the heat pump.

Fig. 1: Heat pump schematically.



Principles

A heat pump extracts heat from a reservoir with the temperature T_1 through vaporization of a coolant and transfers this heat to a reservoir with the temperature T_2 through condensation of the coolant. As a result, the temperature differential $\Delta T = (T_2 - T_1)$ between the two reservoirs increases.

A heat pump can be characterised by the efficiency ε (or performance number) which is greater than one. At first glance, this seems to contradict the law of conservation of energy as the efficiency is the ratio of the quantity of heat ΔQ_2 which is released by the heat pump to the reservoir with the temperature T_2 to the applied electrical energy ΔW:

$$\varepsilon = \frac{\Delta Q_2}{\Delta W} \qquad \text{(I)}$$

ε: efficiency of heat pump (performance number)

ΔQ_2: heat released to the reservoir with T_2

ΔW: applied electrical energy to run the process

This contradiction can be solved if we realize that the applied electrical energy ΔW is used to remove the quantity of heat ΔQ_1 from a reservoir with the low temperature T_1. The law of conservation of energy (all energies are calculated as positive) applies only to the total process:

$$\Delta Q_2 = \Delta Q_1 + \Delta W - \Delta Q_v \qquad \text{(II)}$$

ΔQ_1: heat extracted from the reservoir with temperature T_1

ΔQ_2: heat transferred to the reservoir with temperature T_2

ΔQ_v: heat lost in the process

ΔW: applied electrical energy to run the process

ΔQ_v symbolizes the heat which is lost from the compressor or the heat pump pipelines to the environment.

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The efficiency ε can only be greater than one when the heat is transported by the coolant from the side where the evaporation takes place to the side where the liquefying takes place.

The aim of this experiment is to determine the efficiency ε of the heat pump as a function of the temperature differential ΔT = ($T_2 - T_1$). By determining the influence of the temperature differential between warm and cold reservoirs the importance of the heat reserves on the evaporation side for the efficiency. is shown.

The two heat reservoirs are represented by water vessels. With the temperature T_1 in the vessel with the cold water and the temperature T_2 in the vessel with the warm water the heat efficiency $\Delta Q_2/\Delta t$ of the heat pump is given by:

$$\frac{\Delta Q_2}{\Delta t} = \frac{\Delta T_2}{\Delta t} \cdot m \cdot c \qquad \text{(III)}$$

m: mass of water in the warm container

c: specific heat capacity of H_2O

Δt: interval of measuring time

$\Delta T_2 = T_2 - T_0$ (T_0: temperature of warm and cold vessel at start)

With equation (III) the efficiency is given by:

$$\varepsilon = \frac{\Delta Q_2}{P \cdot \Delta t} \qquad \text{(IV)}$$

The heat quantity ΔQ_2 released is determined from the heating of water reservoir T_2, while the applied electrical energy ΔW is measured using the Joule and Watt Meter.

Apparatus

1 Heat pump..389 521
1 Joule and Watt Meter 531 831
1 Digital Thermometer..666 209
2 Temperature Sensor, NiCr-Ni............................666 193
1 Digital stopwatch 313 12

Additionally recommended:

RS 232 cable, 9-pole...729 769

additionally required:

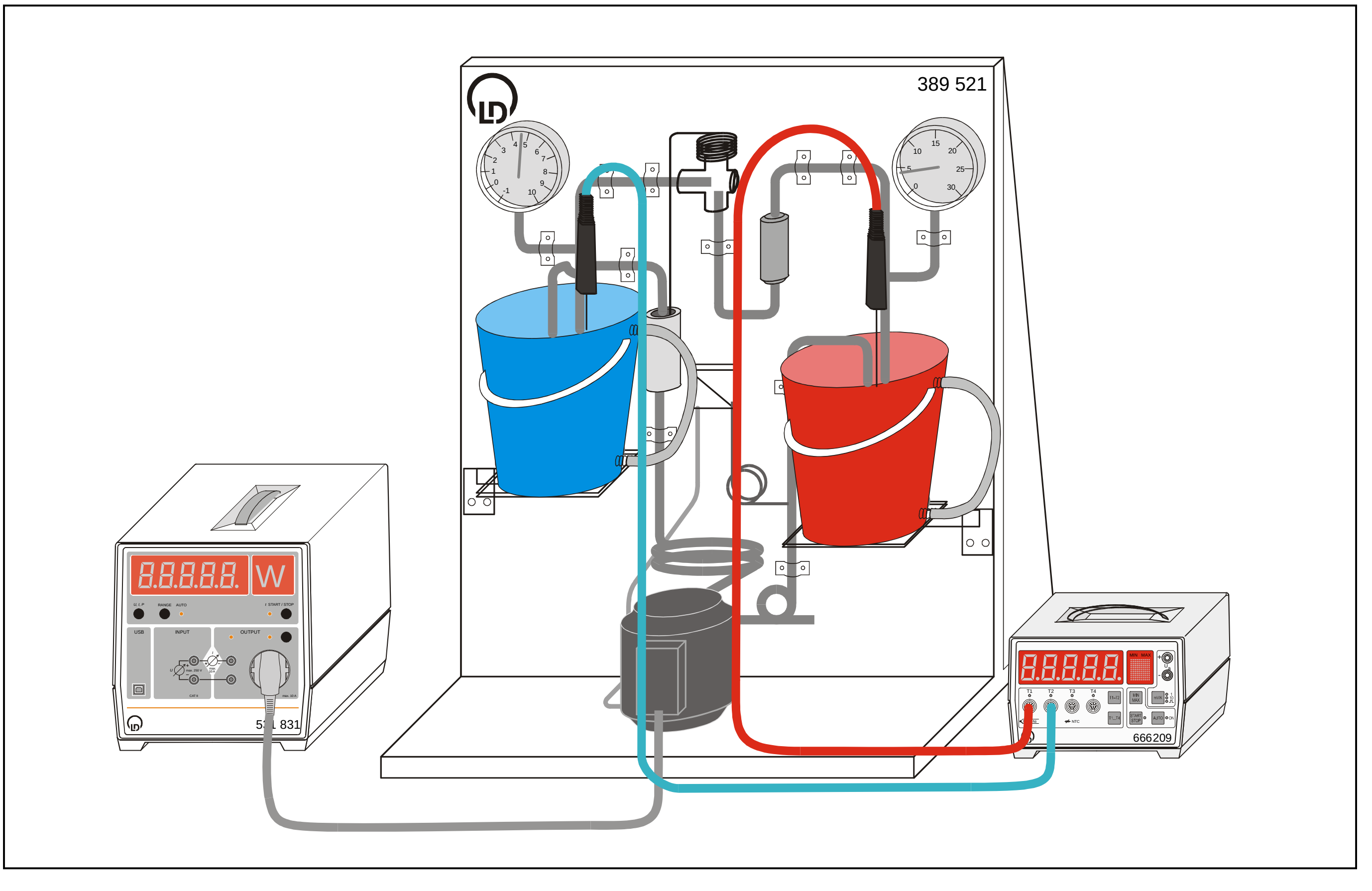
1 PC with Windows 98 or higher

Setup

The experimental setup of the apparatus is shown in Fig. 2.

- Connect the top and bottom hose nipples of each vessel using the section tube. (Alternatively, establish an appropriate hose connections between the water vessels and the external water circuit.)
- Fill each vessel with water up to the 4 liter mark. Fold up the supports (i.e. trays) for the vessels and place the water vessels in their experiment positions around the copper tube windings, then fold the supports again and rest the water vessels on them.
- Attach the thermometer holders to the cupper tubes above the liquefier and vaporizer. Insert the temperature sensors in the plastic tubes of the thermometer holders.

Fig. 2: Experimental setup schematically.



Safety notes

Mind the safety notes of the instruction sheet 389 521 for the heat pump.

- The coolant circuit is pressureized. Do not attempt to open this circuit under any circumstances.
- Do not thermally insulate the compressor; this can cause the device overheat.

- Connect the temperature sensors to the digital thermometer.
- Connect the compressor of the heat pump to the Joule and Watt Meter.
- After switching on the Joule and Watt Meter press the black button in the output panel to start experiment. Set the appropriate measuring range by using the toggle buttons “U,I,P” and “Range”.
- Let the experiment warm up for approximately 10 min bring the compressor up to its operating temperature. Then disconnect the heat pump from Joule and Watt Meter and renew the water in each vessel.

For further information and detailed description of the function of the heat pump refer to the instruction sheet 389 521.

Carrying out the experiment

a) Manual recording

- Connect the heat pup again to the Joule and Watt Meter.
- Note the temperature of the cold and warm water vessel every 30 sec. using the automatic switching function of the digital thermometer.
- Read off the power P of the compressor on the Joule and Watt Meter.
- Continuously and slowly stir the water in the cold and warm vessel during the experiment.

b) Automatic recording

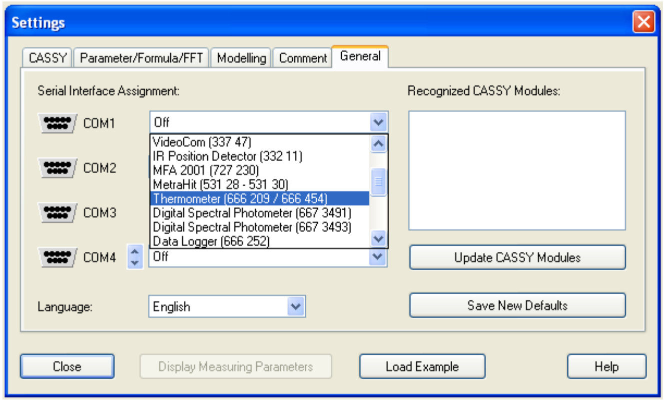
When using the RS 232 connection cable the recorded data by the Digital Thermometer can be transferred to the computer.

- If not yet installed install the software and open the software (preconfigured CASSY Lab user interface).

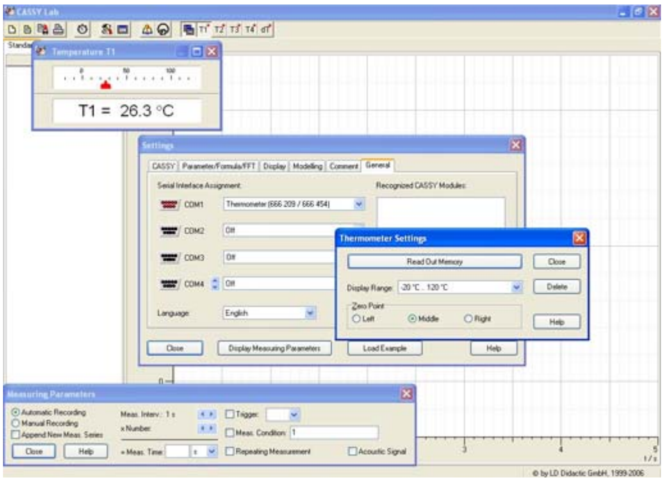
Note: The software CASSY Lab for data recording with the Digital Thermometer can also be downloaded from http://www.ld-didactic.com/

- Open the window “Settings” using the tool box button or function key F5 from the top button bar:

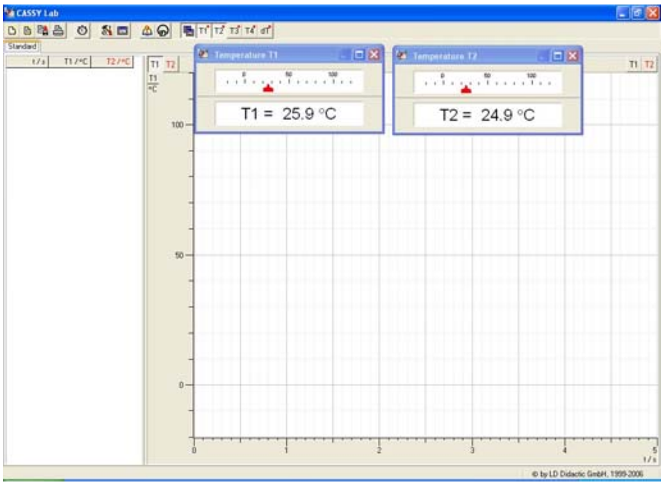
- Select the tab “General” in the window “Settings” and set the appropriate COM port by selecting the “Thermometer” detector:



- After selecting the “Thermometer” for the appropriate Com port the software opens a table, a display and various windows: indicator for the temperature T1, the window “Thermometer Settings”, the window “Settings” and the window “Measuring Parameters”:



- Accept the preset values by closing all windows inside the main window.
- To display the temperature T2 click on the button



Note: A measurement can be cleared with the button or the function key F4.

- Press the button or function key F9 to start recording the temperature as function of time.

Note: The button works as a toggle switch. The data acquisition can be stopped by pressing or F9.

- Continuously and slowly stir the water in the cold and warm vessel during the experiment.

Note: Good result for ΔT_2 can be obtained only when properly stirred during performing the experiment.

Measuring example

a) Manual recording

Table 1: Temperature T_1 and T_2 as function of time t.

$\frac{t}{s}$	$\frac{T_1}{s}$	$\frac{T_2}{s}$
0	14.9	16.6
30	14.4	17.3
60	13.3	18.2
90	12.6	18.9
120	12.1	19.7
150	11.6	20.3
180	10.9	21
210	10.5	21.5
240	9.8	22.3
270	9.3	22.8
300	8.8	23.5
330	8.4	24
360	7.9	24.6
390	7.6	25.2
420	7.1	25.8
450	6.6	26.3
480	6.2	26.7
510	5.9	27.3
540	5.5	27.8
570	5.1	28.3
600	4.7	28.8
630	4.3	29.3
660	4	29.8
690	3.6	30.1
720	3.3	30.6
750	3	31.1
780	2.6	31.5
810	2.4	31.9
840	2.1	32.3
870	1.7	32.7
900	1.5	33.1
930	1.2	33.5
960	1	33.9
990	0.8	34.2

b) Automatic recording

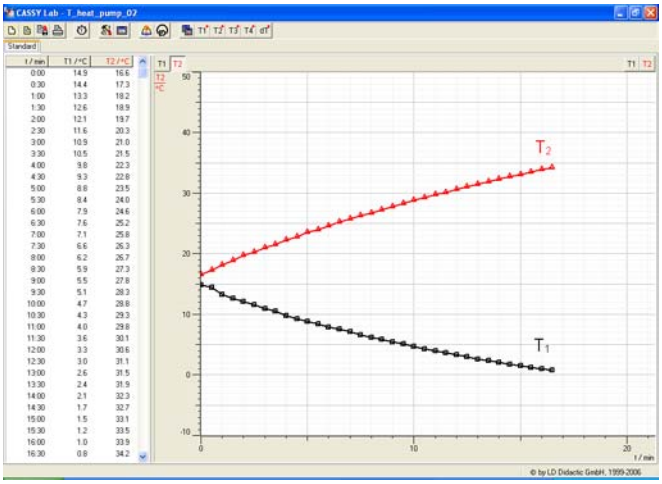


Fig. 3: Temperature in the cold water (T_1) vessel and warm water vessel (T_2) as function of time.

Note: You may label the plot using short cut key Alt-T.

Note: You may save your measurements by pressing the button or using the function key F2.

Evaluation

a) Manual recording

With the

mass of the water m = 4 kg

and specific heat capacity of water $c(H_2O) = 4.19 \cdot 10^3 \ \frac{J}{kg\,K}$

the heat efficiency can be calculated using equation (III).

With the

power P = 125 W

the efficiency of heat pump (performance number) can be calculated using equation (III) and (IV).

$$\varepsilon = \frac{\Delta T_2}{P \cdot \Delta t} \cdot c \cdot m \qquad \text{(VI)}$$

Table 2 shows the efficiency ε as function of $\Delta T = (T_2 - T_1)$.

b) Automatic recording

- Press the button or function key F5 and select the tab "Parameter/Formula/FFT" (Fig. 5).
- Click on the button "New Quantity" to evaluate $\Delta T = (T_2 - T_1)$.
- Select "Formula" and type "T2 – T1" to define ΔT
- Enter "&D" to define the symbol ΔT

Note: The character "&" activates the Greek symbol.

- Enter the unit K and the values for the range, e.g. "0" to "35"

Note: These values define the range to be displayed when plotting the values in a display (see below).

Table 2: The efficiency of the heat pump ε as function of $\Delta T = (T_2 - T_1)$. The efficiency was evaluated for a constant power 125 W and water mass of 4 kg.

$\frac{\Delta T}{K}$	$\frac{\Delta T_2}{K}$	ε
1.7	1.6	–
2.9	2.3	10.279
4.9	3.2	7.151
6.3	3.9	5.810
7.6	4.7	5.251
8.7	5.3	4.737
10.1	6	4.469
11.0	6.5	4.150
12.5	7.3	4.078
13.5	7.8	3.873
14.7	8.5	3.799
15.6	9	3.657
16.7	9.6	3.575
17.6	10.2	3.507
18.7	10.8	3.448
19.7	11.3	3.367
20.5	11.7	3.268
21.4	12.3	3.234
22.3	12.8	3.178
23.2	13.3	3.129
24.1	13.8	3.084
25.0	14.3	3.043
25.8	14.8	3.007
26.5	15.1	2.934
27.3	15.6	2.905
28.1	16.1	2.878
28.9	16.5	2.836
29.5	16.9	2.797
30.2	17.3	2.761
31.0	17.7	2.728
31.6	18.1	2.696
32.3	18.5	2.667
32.9	18.9	2.640
33.4	19.2	2.600

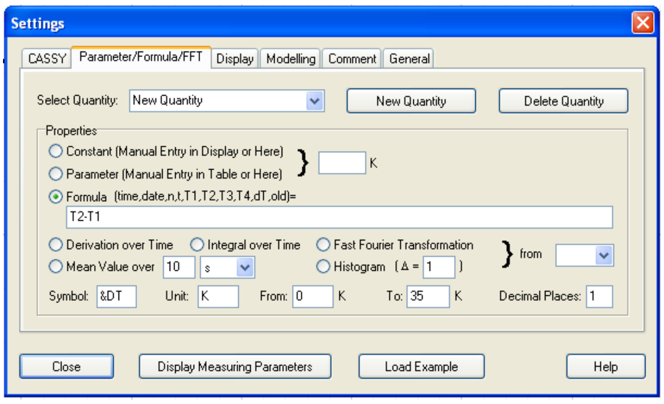


Fig. 4: Defining the formula $\Delta T = (T_2 - T_1)$ by using the new quantity tool (function key F5).

- If the window "Settings" is not open press the button or function key F5 and select the tab "Parameter/Formula/FFT" (Fig. 5).
- Click on the button "New Quantity" to evaluate the efficiency ε of the heat pump.
- To define ε select "Formula" and enter (i.e. equation (VI)):

  4.19·1000*4/(&DT*125)

- Enter "&e" to define the symbol ε
- Enter the values for the range, e.g. "0" to "12" and choose 3 decimal spaces.

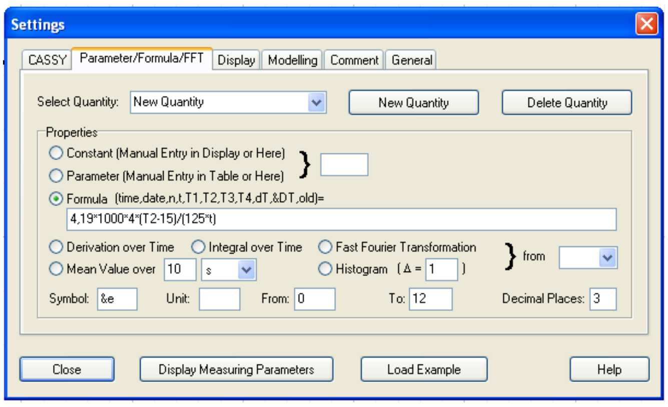


Fig. 5: Defining the formula $\Delta T = (T_2 - T_1)$ by using the new quantity tool (function key F5).

To plot ε as function of ΔT you may proceed as follows:

- Press the button or function key F5 and select the tab "Display" (Fig. 6).
- Click on the button "New Display"
- Enter a name, e.g. "Evaluation"
- Select ΔT for the X-axis and ε for the Y-axis
- Close the window "Settings" and select the tab "Evaluation (Fig. 7).

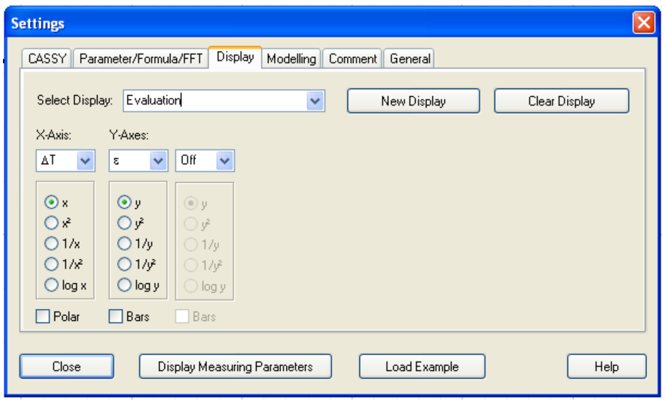


Fig. 6: Defining a new “display” to plot the efficiency ε of the heat pump as function of ΔT by using the new display tool (function key F5).

Note: You may save these settings by pressing the button or using the function key F2.

Note: To change the settings or copy the data click with the right mouse button on the display, tables and axes to open the desired pop up menu.

Results

Fig. 3 shows the temperature T_1 and T_2 as function of time.

In Fig. 7 the efficiency of the heat pump is plotted as function of $\Delta T = (T_2 - T_1)$.

The efficiency of the heat pump (coefficient of performance) $\varepsilon(\Delta T)$ decreases with the increasing temperature difference $\Delta T = (T_2 - T_1)$ between liquefier and vaporizer (Fig. 4), because the $T_2(t)$ diagram levels off with increasing temperature difference. At high temperatures, factors contributing to this leveling-off include heat losses due to water evaporation, heat radiation and conduction of the compressor and the tubes between compressor and liquefier; their influence cannot be quantitatively determined here.

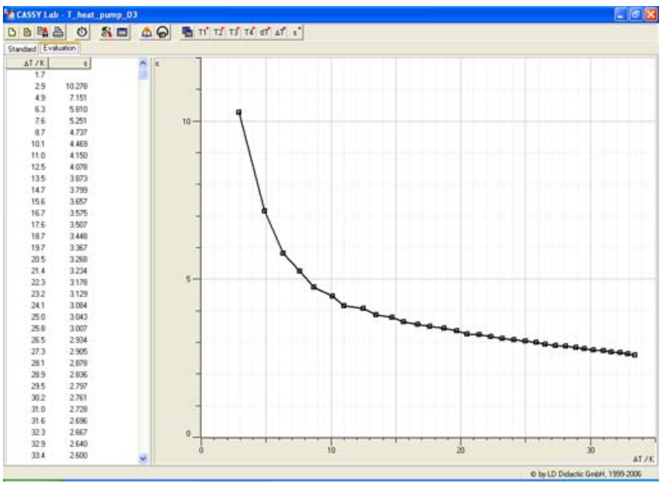


Fig. 7: Defining a new “display” to plot the efficiency ε of the heat pump as function of ΔT by using the new display tool (function key F5).

Supplementary information

The efficiency of the heat pump can be optimized by:

1. Thermally insulate the water vessels and the tubes (but not the compressor!), e.g. with strips of foam rubber.
2. Before starting the experiment, bring the compressor up to its operating temperature (let it run for approx. 10 minutes), then replace the water in each vessels and start the experiment.