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Experiment 7

Studying the properties of heat pump working with a solar collector

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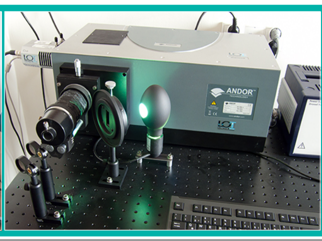
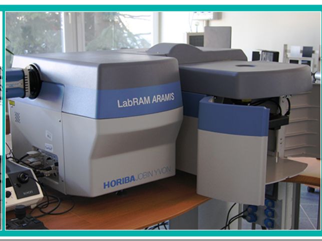
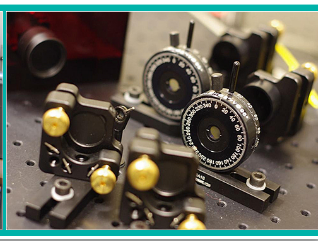






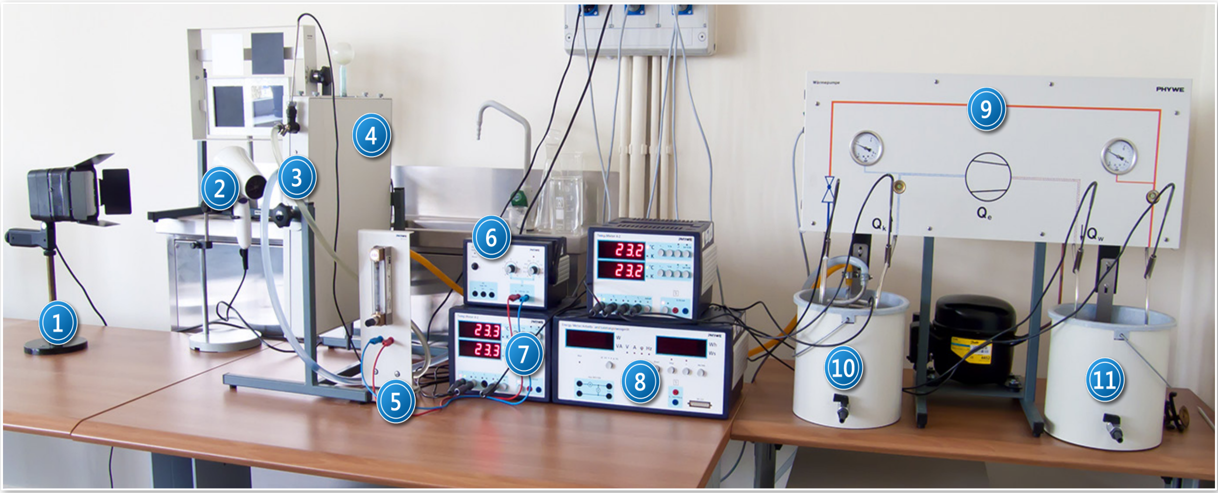
I. Background theory.

1. Heat transfer processes:
   a) heat conduction;
   b) radiation;
   c) diffusion.
2. Solar electromagnetic radiation.
3. Greenhouse effect.
4. Solar collector:
   a) types of collectors;
   b) design and operation of solar collectors;
   c) collector efficiency.
5. Fundamentals of thermodynamics:
   a) thermodynamic processes for gases;
   b) thermodynamic principles;
   c) thermodynamic system;
   d) reversible and irreversible processes;
   e) Joule – Thomson effect.
6. Heat pumps:
   a) distribution of heat pumps;
   b) design and operation of a heat pump;
   c) efficiency and power of a heat pump.
7. Solar thermal installations.
8. Experimental set-up and overview.

II. Experimental tasks.

1. Refer to the measuring system in *Picture 1* and the procedures given in the *Appendix*.
2. Determine the water efficiency of the solar collector.
3. Determine the heat pump efficiency.
4. Determine the overall pump – collector efficiency.

> **Hint**
>
> **Steps II.2. – IL.4. should be performed according to the detailed instructions given in the *Appendix*.**



Picture 1. Heat pump – solar collector experimental set-up: 1 – halogen lamp; 2 – hair-dryer; 3 – thermocouple probe; 4 – solar collector; 5 – water pump with flow-metre; 6 – water pump power supply; 7 – digital thermometer; 8 – electrical energy, power and time metre; 9 – heat pump; 10 – heat exchanger and evaporator reservoir; 11 – reservoir with condenser.

III. Apparatus.

1. Solar collector.
2. Heat pump.
3. Evaporator.
4. Condenser.
5. Heat exchanger.
6. Exchanger reservoir.
7. Halogen lamp with a power of 1 kW.
8. Digital thermometer.
9. Electrical energy, power and time meter.
10. Thermocouple probes.
11. Water pump with power supply.
12. Hair dryer.
13. Heater.
14. Tape measure.
15. Stopwatch.

IV. Literature.

1. PHYWE Systeme GmbH & Co.KG – "*Solar Ray Collector*", Laboratory Experiments, Physics 3.6.01- 00, 2008.
2. L. Andrèn – "*Solar Installations. Practical Applications for the Built Environment*", James & James Science Publishers, London 2003.
3. R. Eisberg, R. Resnick – "*Quantum Physics of Atom, Molecules, Solids, Nuclei and Particles*", John Wiley & Sons Ltd, New York 1985.
4. D. Halliday, R. Resnick, J. Walker – *"Fundamentals of Physics"*, John Wiley & Sons Ltd, New York 2001.
5. M. Fox – "*Optical Properties of Solid*", *Oxford* University Press, Oxford 2001.

Appendix

The experiment

I. Taking temperature measurements for inlet temperature $T_{IN} \approx 20\ ^0C$ with the lamp on.

1. Fill the heat exchanger reservoir with water (10 in *Picture 1*) such that the heat exchanger coils are completely submerged. Carefully stir the bath.
2. Place the heater in a beaker. While stirring, heat the water to a temperature of about 20 ^0C, then turn off the heater. During subsequent steps of the experiment, stir the water in the reservoir regularly to maintain a constant water temperature at the inlet.
3. Set the halogen lamp at a distance of 70 cm from the collector such that the collector is perpendicular to the direction of the incident light.
   Turn on the lamp.

ATTENTION!

The lamp housing becomes extremely hot! Do not touch it or obstruct its ventilation gratings.

Turn the lamp off immediately after completing measurements.

4. Turn the water pump power (*Picture 2*) and set the voltage knob to 4 V, and the current limiter knob to 1 A.
5. Use the water pump valve to set the flow rate to 100 cm^3/min. When taking measurements, continuously monitor the rate of water flow in the collector circuit.

Picture 2. Circulation pump: 1 - flow rate control valve;
2 - flow indicator.

6. With a digital temperature meter (*Picture 3*), note the temperatures at the inlet T_{IN} and outlet T_{OUT} of the collector, and the temperature in the heat exchanger reservoir T_R every minute for 30 minutes. Stir the water in the reservoir after each measurement.

Picture 3. Digital thermometer: 1 - displays indicating the temperature of the selected input channel; 2 - input channels, glowing red light – measured temperature is displayed on the upper display, green lights – on the lower display; 3 - channel control buttons, from the left: change the input channel, change temperature scale, change mode, zero setting; 4 – temperature scale indicator.

7. Turn off the lamp after taking the final reading.
8. Repeat the measurements from I. 6. in the *Appendix* for the collector without glass and rear plates.
9. Twist the pump's power supply voltage knob to the minimum and then turn off the water pump.
10. Empty the water tank with the drainage tap.
11. Based on the results obtained, plot graphs of temperatures T_{IN}, T_{OUT} and T_R as a function of time on the same set of axes.
12. Calculate the differences in temperature at the inlet and outlet manifold.
13. Calculate the efficiency of the collector using the formula:

$$\eta = \frac{c_w \dot{m}(T_{OUT} - T_{IN})}{qA} \quad , \qquad (1)$$

where: T_{OUT} – collector outlet temperature;

T_{IN} – collector inlet temperature;

c_w – specific heat of water, c_w = 4186 J/kg·K;

$\dot{m}$– water flow velocity, $\dot{m}_1$ = 100 g/min, $\dot{m}_2$ = 200 g/min;

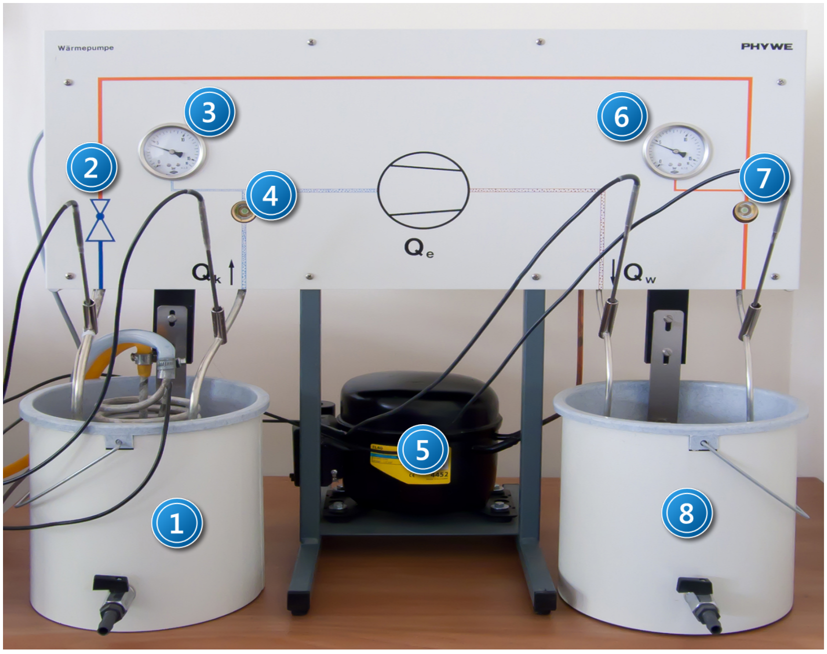
A – collector surface area, A = 0,12 m^2;

q – incident light intensity at a distance of 70 cm from the collector, q = 1 kW/m^2 .

Calculate the errors in the collector efficiency.

II. Determining heat pump efficiency.

1. Fill the reservoirs (1 and 8 in *Picture 4*) with cold water (about 10 ^{0}C) to the marked level, completely submerging the heat exchanger coils. Ensure that the condenser tank water is not colder than the water in the evaporator tank.
   Stir the water in the reservoirs.



Picture 4. Heat pump: 1 – evaporator reservoir; 2 – expansion valve; 3 – manometer to measure the medium's pressure after leaving the evaporator; 4 – window for observing the working medium's state after leaving the evaporator; 5 – working medium compressor; 6 – manometer to measure the medium's pressure after leaving the condenser; 7 – window for observing the working medium's state after leaving the condenser; 8 – reservoir with condenser.

2. Take measurements:

- condenser pressure p_1 (manometer (6)) and evaporator pressure p_2 (manometer (3));
- evaporator tank water temperature T_1 and condenser tank water temperature T_2;
- coolant temperature at the evaporator inlet T_P^{IN} and outlet T_P^{OUT}, coolant temperature at the condenser inlet T_S^{IN} and outlet T_S^{OUT}.

3. Turn on the pump power supply.
4. Take measurements of p_1, p_2, T_1, T_2, T_P^{IN}, T_P^{OUT}, T_S^{IN}, T_S^{OUT} every 2 minutes for 30 minutes and observe the power meter.

ATTENTION!

Stir the water in both reservoirs after each measurement.

5. Turn on the heat pump.
6. Take a reading of electrical energy (*Picture 5*) and reset the meter.

Picture 5. Electrical energy, power and time meter: 1 – power display; 2 – voltmeter function selector; 3 – "RESET" button; 4 –"STOP" button; 5 – button to select energy units; 6 – displays electricity consumed by the pump.

7. Empty the water tanks using the drainage taps.
8. Plot a graph of temperatures as a function of time on the same set of axes.
9. Determine the value of changes in water temperature per unit time $\frac{\Delta T}{\Delta t}$ for the functions $T_1(t)$ and $T_2(t)$ using the polynomial approximation method based on experimental results. Tabulate your results.
   Determine the magnitude of identified errors.
   Interpret the results.
10. Calculate the efficiency of the pump by using the formula:

$$\varepsilon = \frac{\dot{Q}}{P} = \frac{c_w m_w}{P}\frac{\Delta T_1}{\Delta t} \tag{2}$$

where: $\dot{Q}$ – heat flow through the condenser, $\dot{Q} = c_w m_w \frac{\Delta T_1}{\Delta t}$;

P – compressor power, P = 120 W;

c_w – specific heat capacity of water, c_w = 4182 J/kg·K;

m_w – mass of water, V = 3,9 dm^3;

$\frac{\Delta T}{\Delta t}$ – temperature change per unit time.

11. Read off pressures p_1 and p_2 from the measurement results for time *t* = 10 min.
12. From *Table 1.*, read off the specific enthalpy h_1 and the specific volume v corresponding to pressures p_2 of the vapour coolant and the specific enthalpy h_3 corresponding to pressures p_1 of the liquid coolant.
    Add atmospheric pressure of 1 bar (1 bar = 10^5 Pa) to the manometer readings.
13. Calculate the volumetric efficiency of the compressor using the formula:

$$\lambda = \dot{V}/\dot{V_g} \quad , \tag{3}$$

where: $\dot{V}$ – flow rate of the working medium by the compressor, $\dot{V} = \nu \frac{\dot{Q}}{h_1 - h_3}$;

$\dot{Q}$ – flow rate of heat absorbed by the evaporator;

ν – specific volume of working medium vapour;

h_1 – vapour coolant enthalpy;

h_3 – liquid coolant enthalpy;

$\dot{V_g}$ – geometric flow, $\dot{V_g} = V_g f$;

V_g – compressor displacement, $V_g = 5{,}08\ \mathrm{cm}^3$;

f – compressor piston revolutions per minute, f = 1450 min^{-1}.

Table 1. Pump coolant parameters: Θ – temperature, p – absolute pressure, v – vapour specific volume, h' – liquid specific enthalpy, h" – vapour specific enthalpy.

Θ °C	p MPa	v m³/kg	h' kJ/kg	h" kJ/kg
-30	0.08436	0.22596	161.10	380.45
-20	0.13268	0.14744	173.82	386.66
-10	0.20052	0.09963	186.78	392.75
-8	0.21684	0.09246	189.40	393.95
-6	0.23418	0.08591	192.03	395.15
-4	0.25257	0.07991	194.68	396.33
-2	0.27206	0.07440	197.33	397.51
0	0.29269	0.06935	200.00	398.68
2	0.31450	0.06470	202.68	399.84
4	0.33755	0.06042	205.37	401.00
6	0.36186	0.05648	208.08	402.14
8	0.38749	0.05238	210.80	403.27
10	0.41449	0.04948	213.53	404.40
12	0.44289	0.04636	216.27	405.51
14	0.47276	0.04348	219.03	406.61
16	0.50413	0.04081	221.80	407.70
18	0.53706	0.03833	224.59	408.78
20	0.57159	0.03603	227.40	409.84
22	0.60777	0.03388	230.21	410.89
24	0.64566	0.03189	233.05	411.93
26	0.68531	0.03003	235.90	412.95
28	0.72676	0.02829	238.77	413.95
30	0.77008	0.02667	241.65	414.94
32	0.81530	0.02516	244.55	415.90
34	0.86250	0.02374	247.47	416.85
36	0.91172	0.02241	250.41	417.78
38	0.96301	0.02116	253.37	418.69
40	1.0165	0.01999	256.35	419.58
42	1.0721	0.01890	259.35	420.44
44	1.1300	0.01786	262.38	421.28
46	1.1901	0.01689	265.42	422.09
48	1.2527	0.01598	268.49	422.88
50	1.3177	0.01511	271.59	423.63
60	1.6815	0.01146	287.49	426.86
70	2.1165	0.00867	304.29	428.89

III. Studying the collector – pump unit.

1. Turn on the water pump power supply and set the voltage to 4 V.
2. Prepare the heat pump according to II.1 in the *Appendix*.
3. Open the pump circulation valve.
4. Observing the meter, wait until the inlet and outlet temperatures, T_{IN} and T_{OUT} respectively, are constant and equal.
5. Set the flow rate to 100 cm^3/min using the circulation valve. Monitor the flow rate continuously during measurements.
6. Turn on power to the pump.
7. Record temperatures T_{IN} at the collector inlet, T_{OUT} at the collector outlet, condenser water temperature T_1 and evaporator water temperature T_2 each minute until the temperature T_1 reaches 0 ^{0}C.

ATTENTION!

During measurements, stir the water in both reservoirs approximately every 2 minutes.

8. Turn off the heat pump.
9. Drain the water using the drainage taps.
10. Plot a graph of T_{IN} and T_{OUT} as a function of time on the same set of axes.
11. Calculate the collector efficiency for each temperature reading using the formula:

$$\eta = \frac{P_U}{AP_i} = \frac{\dot{m}c_w}{AP_i}(T_{OUT} - T_{IN})$$

where: P_U – net power, used by the collector;

P_i – radiation power density incident on the collector;

A – collector surface area, A = 0,12 m^2;

$\dot{m}$ – water mass flow rate, $\dot{m}$=100 g/min;

c_w – specific heat capacity of water, c_w = 4182 J/kg·K;

T_{IN} – collector inlet water temperature;

T_{OUT} – collector outlet water temperature.

Include the results of the calculations in the table.

Determine the magnitude of identified errors.

Interpret your results.

12. Determine the pump efficiency ε according to II.8. – II.10. in the *Appendix.*
13. Ensure that the halogen lamp is located 70 cm from the collector and that the collector is perpendicular to the incident light.
14. Repeat steps II.2. – II.12. in the *Appendix*.

    Simultaneously turn on the stopwatch, lamp and pump.

ATTENTION!

The lamp housing becomes extremely hot! Do not touch it or obstruct its ventilation gratings.

15. Turn off the lamp after taking your final measurements.
    Twist the pump's power supply voltage knob to the minimum and then turn off the water pump.
16. Analyse the results, indicating all factors which may affect the efficiencies of each device.