Renewable Energy Online
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Renewable Energy Laboratories and Excursion

Lehrbrief

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Renewable Energy Online

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Renewable Energy
Laboratories and Excursion

edited by

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Learning objectives

After processing this chapter

- you can explain what science is
- you can name the characteristic parts of a lab report
- you can describe the difference between report, paper and thesis

2.1 Good Scientific Practice

Welcome to the magnificent Building of Science. My name is Bubu and I will be your guide. But before we climb to the higher levels of this tower let us stop for a moment and take a look around because even from here the view is already beautiful.

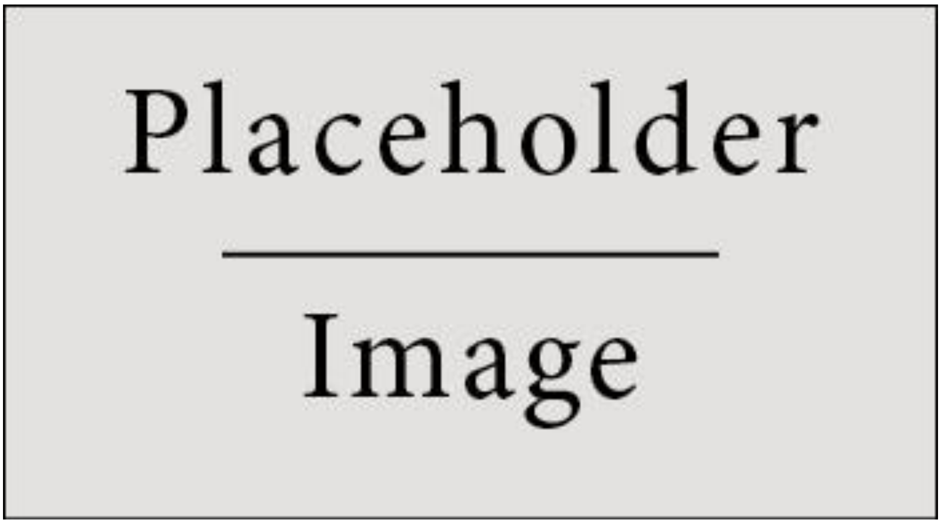


Figure 2.1: The Building of Science and its guardian spirit Bubu

If you're not afraid of heights may I ask you to look below. As you can see the tower hovers over a huge bottomless gap in the earth. We call it the Maw of Irrelevance and what falls into it, will be gone forever. The tower is held up only by the strong Axiom Chains which our ancestors have set up generations ago and would they break the whole Building of Science might fall into the Maw.

Only once one of the chains had experienced so much strain that it almost broke and put the whole Building into immense danger. You can see the chain of Thermodynamics to the east where the Sun just rises and in the middle of it one chain link shines brighter than the others.

This is Planck's link and it was forged by the sharpest minds of their time. Only their combined efforts kept the Building from collapsing.

Maybe if you look closely you can see the path you have taken from the far lands where you have come from. See where you have reached the Maw and climbed over one of the Axiom Chains to reach the base of the tower. All of you have taken very different routes to reach this level but to the next level you will climb together. However, only a little further way up the tower will split into several pinnacles and you will have to choose your own path again.

In order to become masters of your science you will not only learn about the substance the Building of Science is constructed of, you will also learn the necessary skills to become a builder yourself, an architect of future towers which will be built upon the base you are climbing now. For now when still learning your craft you will not yet build new towers but you will strengthen the walls that already stand. But always remember when you do not apply the ancient Crafts of our Art and you build something which in not firmly connected to the Building your work will fall down into the Maw of Irrelevance.

What is science?

Science is basically the product of scientists just like buildings are the products of architects. However, it can be argued that science is more than pure knowledge. It is knowledge of a certain quality. Just like a layman can construct a makeshift housing it is certainly of lower quality than a building planned and constructed using the tried methods of architects. Knowledge becomes science when it was gained by scientific methods.

The qualities knowledge must possess in order to be considered science are that it was gained reproducibly by clearly defined methods (Measurement and Analysis). The knowledge must be put in relation with previous knowledge either to confirm, conflict or expand on previous ideas (Discussion). Notice that by the last condition simple knowledge does not apply for science. However, it can act as hypothesis for further observations. The repeated observation of a phenomenon which is put into relation to previous observations then slowly turns into scientific knowledge. However, science is more than just observation and description of a phenomenon. Scientists try to find more general models which describe the phenomenon and thus make assumptions about phenomena which have not yet been observed. The more often a phenomenon is observed, interpreted and modeled in the same fashion the stronger the model describing the phenomenon becomes and will support those ideas which expand on it (hypothesis ! theory). However, theories are always construction sites and will never be infallible as the very first brick was only a simple observation itself to which the rest of the whole building is only put in relation to. Scientific theories try to answer the question of causality thus expanding knowledge and strengthen the building, while being aware that the original causality mightnever be found.

However, knowledge does not necessarily need to expand on previous knowledge and even expanding knowledge does not necessarily expand the building of science. If the links between scientific knowledge break the knowledge is lost und without value to the building of science. Research in the ivory tower which is not communicated, knowledge which is presented in a way that it is not or wrongly received or knowledge which is lost in time might still be science but worthless for the building of science. Therefore it is of the utmost importance to communicate scientific knowledge, present it in an understandable fashion and ensure that the links cannot easily be broken.

Notice that in the laboratories you will usually not generate new knowledge and not expand the building of science. This is rather done when you have climbed up on one of the infinite towers of the building and will be the subject of your master thesis. But you are not there yet, for now the labs shall help you climb the building. But you will have to build some of the stairs for yourself and these have to be connected to the building and in a sense they will actually strengthen the whole building as they are repeated observations. So try to see the labs as stairs which shall help you reach another level on your way to the top of the tower. Just make sure that your stairs will be fixed well to the building by good scientific reporting.

Pillars of Science

Within the laboratories and seminars of our programme you shall learn and improve your scientific skills. This section elaborates upon those aspects which are important for scientific work to be considered as such (Pillars of Science). Just like the supporting beams in a building these pillars and their relative position to each other will hold up the building. Consider the work in the laboratories as more than just sitting in the lab and understand how all of these pillars are required to support your work.

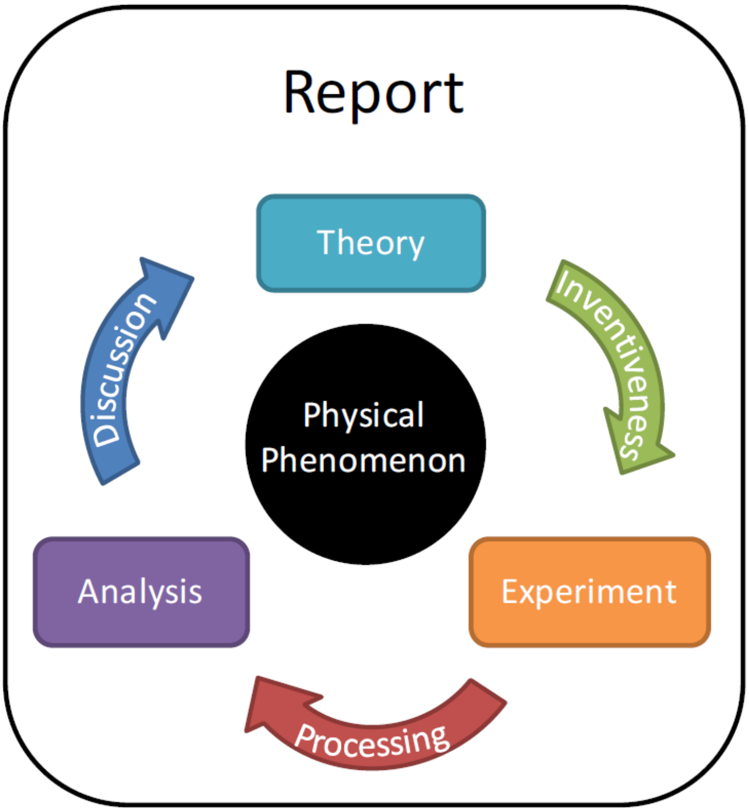


Figure 2.2: Pillars of Science

The Pillars of Science are Theory, Measurement and Analysis. Note how they surround the physical phenomenon and relate to each other in Fig. 1.2. In order to build a tower around the phenomenon you can start with any pillar just make sure to make a full loop.

Theory

In order to reap the full benefit from performing the experiments in the laboratories or projects in the seminars, we expect you to have a basic theoretical understanding of the phenomenon or problem, as it will form the basis for discussion. Yet, we want to point out that even though theoretical models can describe a phenomenon very mathematically smooth they are not necessarily correct. Models are constructs which merely approximate reality as well as we are able to describe it. Depending on the sophistication of a model it is isolated or takes into account multiple environmental factors which, however, more often than not might not even be known beforehand.

Inventiveness

Any phenomenon must be detected via sensors that might already be part of the human body or first be transformed into a signal we can detect. Often there are physical principles behind the transformation processes of the sensors which might only slightly be related to the physical phenomenon under investigation. We will require inventiveness to conceive a strategy or a method to measure a phenomenon. This connects the pillar of theory with the pillar of the measurement. In order to judge the value of the measurements you should understand these principles as they often determine the validity of the data. Try to sharpen your inventiveness when reading literature or text books to get an idea on how to approach the measurement on a more abstract level.

Measurement

In laboratories actual measurements are performed which establish the next pillar. Here, you should learn about different measurement techniques and devices. This includes the preparation of the samples under investigation and the calibration of the measurement devices. Hands-on experience of the phenomenon will help you to improve your understanding from the lectures and will also show you the limits of some models. You should also train your methods to work in a lab including keeping a lab-book which will help you when you will later work on your thesis.

Processing

Often the data recorded during the lab-day has to be processed before it can be properly evaluated. For example data in tables has to be plotted in a graph or data has to be retransformed from a voltage reading into the relevant physical quantity we are actually interested in. Train your manual data processing skills and intuition and use the opportunity to become comfortable with different software and evaluation tools.

Analysis

The next pillar is the analysis of the processed data. The analysis of your measurement data will be done in the lab report. During the analysis the data should be presented and described qualitatively and then quantified and fitted to the theoretical models. There exist several analytical methods which are useful in many measurement situations. Some of them are given in the chapters when applicable. This pillar often goes hand in hand with the last aspect.

Discussion

The discussion closes the loop and connects the measurement with the theory. It is maybe the most important aspect to distinguish scientific knowledge from plain observative knowledge and most often ignored by the students in the lab. While you might have fitted your data to theoretical models and extracted certain parameters during the analysis you will need to go a step further in the discussion. This also includes the assessment and estimation of possible error sources and statistics. Try to answer the following questions: What is the significance of our results? Do the measurement results fit to our earlier expectations (hypothesis). Is the model actually applicable or do we need to use another one? Are even the measurement methods themselves valid? Are there any further aspect which might need to be investigated before making a final statement. Do we have suggestions for improvement of the measurements or the models and how do we justify these. The discussion is probably evaded most because during this phase the whole work has to be questioned and justified but it is required in order for your work to become a work of science. Use the opportunity to train this as it will be a vital aspect of your master thesis.

2.2 How to write a report, a paper or a thesis?

All of the aspects mentioned above need to be included in a scientific report to prove the scientific worth of the measurement. Knowledge which is not connected to other knowledge is not relevant as we have stated before. Therefore the seventh skill which includes all of the pillars and their connections is report writing and scientific communication.

If you want to strengthen or expand the building of science you need to publish your results. In a way these publications and the science contained within are the product of scientists. We have emphasized previously that science which is faulty, badly or not communicated at all is of no value and irrelevant. As we do not want our hard work to be irrelevant we have to fulfill the qualities which our gained knowledge must possess to be considered good science.

In the previous sections we identified the qualities, the structure and the methodology good science must possess. In the following, we want to look at the implementation of these aspects in more detail at the example of a lab report. However, principally there is no huge difference between a goodlab report, a thesis and a scientific paper.

The most important properties that your report must possess is reproducibility and transparency. Imagine one of your colleagues who has not yet performed the experiment and has not yet read about it in the reader to be your audience and just from the information in your report should be able to repeat the experiment as you did. Do not take it for granted that the information in the reader is known, however, do not repeat the information which is already given in the reader and not vital to your argumentation. Instead reference the reader and other sources for background information.

Begin your report with a short introduction about the subject of the experiment and its relevance. It serves the very important purpose to generate interest in your research. This section also clears the ground for your research and clarifies where it connects to existing knowledge.

Detail the physical theories and models about the physical phenomenon you have investigated. State and explain the used formulas but basic knowledge or that which exceeds the contents of the lab report should be given by referencing (for example this reader and textbooks). Identify the relevant measurement parameters explain the methodology of their determination. State your expectations here (applied models, reference data).

Explain the specific implementation of the previously detailed measurement methods (setup). This is absolutely mandatory as your specific experiment can only be reproduced with the exact equipment and procedures that were applied by yourself. Give as much information about the used components as possible (manufacturer, model, used ranges, maybe even the serial number) in order to allow for maximum reproducability and transparency. Also explain how the components interact with each other.

Just as important is the specification of your sample. Detail your sample as much possible including its production and treatment history if available. Admittedly it can be almost impossible to know which parameters are important beforehand and often a major part of research will be the identification of the significant parameters just to get reproducable measurements.

Everyone performs the experiment a little different, therefore it is necessary that you explain as detailed as possible your experimental procedure. What have you done? How? If the raw measurement data is of little interest to the analysis please give your measurement tables in the appendix. If you have performed a calibration explain it here.

Often we are not interested in the raw measurement data. Please explain your evaluation procedure and give detail on how to calculate measurement data into data of interest (reference the theory section if applicable). If you have applied complicated fitting procedures explain their background here.

Present your processed and analyzed data (tables, plots) and give a brief description including any special or surprising features. Focus on the data relevant for your argumentation You may include any fits in the same plots as your measurement data.

For a proper scientific report the observations have to be discussed. At least compare the measured data with the expectations you had stated in the theoretical section and discuss if they fit well and if they do give an estimation of how well. If they do not fit well discuss why this might be the case and try to identify the origin of the deviation. Further discuss the significance of your results (error propagation, statistics).

The scientific report usually closes with a brief conclusion of the measurement results and the questions left open. Within a lab report it might be interesting to state what you have learned as students which you did not know or were aware of before. Maybe you even have your own suggestions on how to improve the setup or measurement, please let us know.

At the very end give a list of the used references. Make sure to include them all and use a consistent formatting.

Finally, as we already mentioned above, a lab report, a research paper and a final thesis are principally quite similar forms of scientific communication.

We will discuss that in detail in an online video conference and answer all your questions which you might have. Furthermore, we deepen your knowledge and skills in some practical exercises on scientific writing and reviewing papers.

See you soon online and have fun ☺ !

3 - Laboratories and Excursion

Learning objectives

After processing this chapter and performing the labs and excursion

- you can apply different measurement techniques to acquire data
- you can evaluate and discuss the chosen experimental methods and your data in a scientific manner
- you can communicate your results in form of a lab report

Welcome to the preparation chapter for our first on-campus period at the University of Oldenburg! ☺

We will have different laboratory day, some social events to get to know each other as well as several excursions to e.g. wind energy and photovoltaic plants.

3.1 Labs

The labs will start with an open lab day to introduce or refresh your experimental working skills. During that day, we will investigate temperature and radiation sensors. Then, there will be two lab days to work on two different more complex experiments.

The experiments of this lab course were chosen for distinct reasons. First they are relevant for renewable energies and you should have a sound understanding about them such you will have a strong basis for further discussion and research. You should experience the phenomenon and interact with it and thereby improve your understanding above merely knowing about it from reading or lectures.

All experiments are distributed into four categories: Interaction of Radiation and Matter, Heat Transfer, Fluid Dynamics and Energy Storage (see Figure 3.1). In each category, there are two different experiments offered.

You only have to perform two experiments from two different categories. However, we would like to ask you to choose four of the eight experiments with a ranking regarding your interests. We will try to offer you your two “most wanted”, but due to the limited time of the on-campus phase and the fact that you will do the experiments in groups of two, it could happen, that you might get one experiment of your ranking number three or four.

After we have organized the grouping and assigned two experiments to each of you, we will upload the laboratory reader. This reader should assist you in your preparation for the laboratories and suggests tasks you can do on the lab day. However, as a guide it is by no means all encompassing and you should take it as a starting point for your self-studies and dive deeper into those subjects which you are interested in or where background knowledge might be missing. We try to refer to further literature where appropriate.

As we want to be sure, that all of you are prepared well for the lab day and can benefit in an optimal from the hands-on experience, there will be online interviews some weeks before the on-campus phase for each working group about each assigned lab experiment. These interviews will be done by the mentors who will also be the supervisors during the lab days.

The tasks you will perform on the lab day are not fixed and based on your previous education you might find some laboratories easy or hard. Therefore, only a few tasks will be mandatory

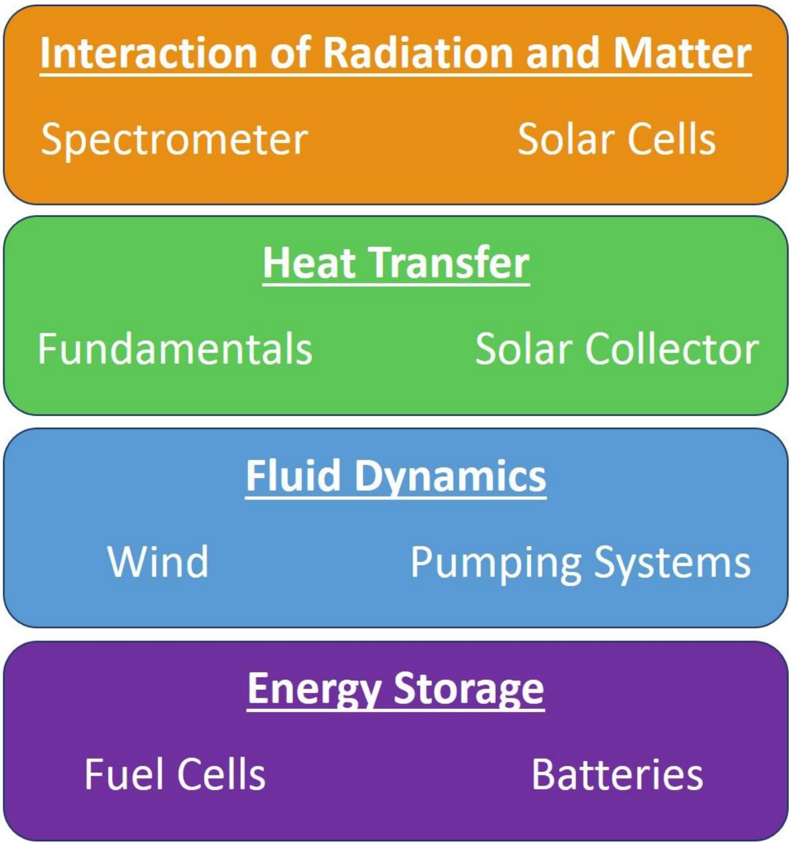


Figure 3.1: Lab experiments in four categories

and further optional tasks of varying difficulty level are suggested. But also feel free to input your own ideas into your lab.

Each chapter of the reader deals with a separate experiment and deals with a physical phenomenon which is relevant for renewable energies. However, part of the learning experience is also understanding several measurement techniques with different devices, evaluation methods, scientific approaches to experiments, error progression, discussion and presentation of your results. So do not restrict yourself to a single aspect but sharpen your overall scientific skills.

The chapters start with a brief introduction of the physical phenomenon, its importance for renewable energies and which measurement techniques will be used. After that follows a background section which will look in more detail at the physical principles and theory behind the phenomenon. We also discuss which parameters will be needed in order to methodologically describe the phenomenon. In this context we will introduce an abstract experimental setup and subsequently go into more detail of the specific instruments used. We will also give information about the measurement principles behind the instruments. Often the measurement data has to be processed to be useful, therefore some analytical methods are given when appropriate.

After the background information the tasks are specified:

> Task 6.7
>
> In these boxes the tasks are specified. If not labeled (Option) they should be performed by each group as these tasks are simply necessary to get reasonable results, e.g. like calibration of your measurement instruments. Later tasks are usually optional, chose those you are interested in. If you have your own ideas please discuss them with your supervisor.

Also possible interview questions are mentioned for each experiment:

6. 6 Interview questions

In these sections you will be given a few questions which you should be able to answer in the preparatory interview. However, these will not be the only questions asked. Prepare for further questions by your supervisor.

Furthermore, there are some feature in the reader to support your learning process:

Every now and then questions appear in the text. Their purpose is to provoke thinking about the topics at hand and shall guide self-reflection. You do not need to answer these questions and sometimes there might not even be a clear and precise answer.

The information given here is important and noteworthy or tries to clarify confusing sections.

The information given here is of the utmost importance as it contains instructions for avoiding harm to you and others or destroying expensive laboratory equipment. Youmust know this information or you will be excluded from the experiment. We do not want to scare you but this is for your own safety.

At the end of each chapter, we refer to further literature and in an appendix give additional information connected to the experiment. This could be datasheets of measurement devices or explanations about alternative measurement methods or devices not featured in our labs.

Finally, after you have performed your experiments during the on-campus phase, there will be several sessions, in which you can work on your first lab report. We all, teachers, supervisors and mentors will support you during this process to make your lab experience be a great success.

And now, we would like to wish you lots of fun and are looking forward to meeting you here in beautiful Oldenburg! ☺

Appendix

The following appendix contains an extract from the lab reader, which will be given to the students before the on-campus period starts.

3 — Solar Cells

Processes between energy states in semiconductors

Learning objectives

After this experiment you will be able to

- explain the basic concepts governing the physics of a solar cell
- measure the characteristic curves of solar cells
- discuss how the characteristic is influenced by environmental parameters
- model the characteristic behavior using a hardware model of a solar cell

3.1 Introduction

Photovoltaics (PV) is the most direct method of converting solar radiation into electricity and therefore a very important technology to harvest the energy of the sun. One benefit of photovoltaic devices is their modularity, i.e. the size of the system can be adjusted well for the need of the consumer and if for example after some time the consumer might require more power the system can be easily expanded.

The basic unit of a photovoltaic system is the solar cell which is composed of several layers of specially designed semiconducting materials sandwiched between two electrodes where the electric current can be collected. A solar panel (or: module) consists of a number of solar cells which are typically connected in series in order to generate an operating voltage high enough to be useful by typical electrical appliances. By connecting multiple solar panels in series or in parallel the output voltage and current can be specially designed to fit any system requirements.

The electric power produced by a solar generator can be consumed directly by a load, used to charge a storage unit (e.g. batteries) or could be fed into the grid via an inverter. However, the connection of a solar generator with a load requires special care, because the generator is no source of constant voltage or constant current as its actual output parameters are strongly influenced by the environmental conditions. Operating voltage and current of a solar generator both depend on the resistance of the load, the intensity of light incident on the cell and to some extent on the temperature of the cell.

In the first part of this laboratory you will investigate this illumination and temperature dependency in a series of experiments on several samples of solar cells. In the second part of this laboratory you will investigate a hardware model of an equivalent circuit of a PV cell. This allows the variation of certain *intrinsic* parameters of solar cells, which are not easily varied in real cells.

3.2 Physical Principles

The energy states in solids are described by energy bands and their physical behavior is mainly determined by the position of their relative position to each other. At temperature $T = 0$ K the electrons fill the energy bands from the lowest energy up until an energy level called the Fermi energy E_F. The energy band which is occupied with the electron with the largest energy is called **valence band** and the band which has the lowest non occupied quantum state is called the **conduction band**. For $T > 0K$ the electrons are distributed over the electron states according to the Fermi distribution.

In metals where the valence band is only partially filled or both bands overlap the electrons can be very easily raised into a conducting state with only a small amount of energy (for example by thermal or optical excitation). In semiconductors and insulators however the valence and the conduction band are energetically separated by an energy gap E_g. Because there are no electron states allowed in the energy gap an excitation requires more energy and is therefore less probable. Therefore the conductivity in these materials is greatly reduced. However the same is also true for the opposite process the relaxation of electrons. In metals it is very probably for an excited charge carrier to find an unoccupied energy state with slightly lower energy which causes the electron to relax into the ground state very quickly (femtoseconds). Because of the energy gap the relaxation is less probable in semiconductors and therefore slower which is required in solar cells so that we have enough time to collect the charge carrier before it relaxes. When an electron is excited it leaves behind a vacancy in the conduction band. We describe this vacancy for reasons of mathematical simplicity by a positively charged particle called a hole which also contributes to the current.

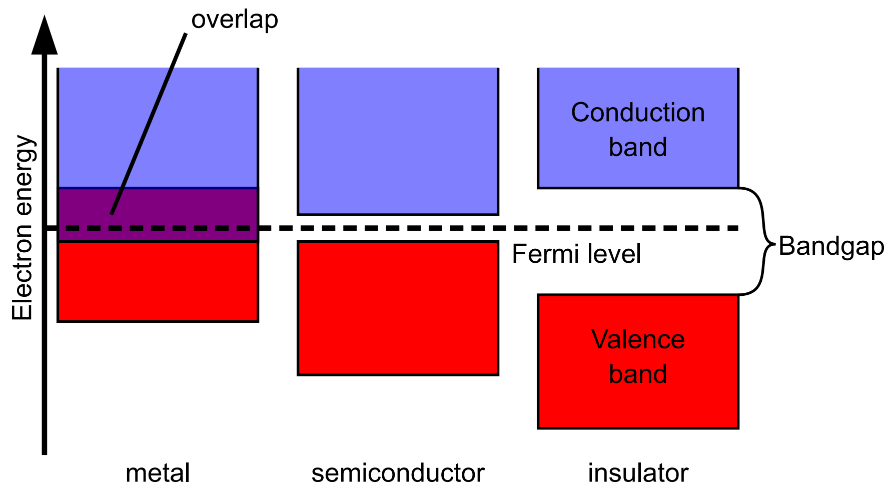


Figure 3.1: Energy bands in metals and semiconductors (source [1])

Yet, the band gap which is so important to collect charge carriers at all has the unfortunate effect that not all radiation can be collected as the photon energy E_{ph} must be: $E_{ph} > E_g$. Reducing the band gap increases the number of photons which can be absorbed and generate charge carriers thereby increasing the current. However, at the same time the probability for the early relaxation of those charge carriers is also increased which consequently decreases the number of charge carriers which can actually be collected. Therefore materials with different band gap energies will vary in their output parameters. The optimum band gap energy considering the AM1.5g solar spectrum has been calculated by SHOCKLEY and QUEISSER to be about 1.7 eV.

In order to collect the charge carriers they need to move to the electrodes. The second necessity in solar cells is therefore a spatial asymmetry causing a gradient which drives the charge carriers out of the semiconductor. This electrochemical gradient can be caused by an electric field and/or a difference in charge carrier concentration and is typically realized by stacking two or more differently designed semiconductors on top of each other. In the widely used silicon solar cells this is achieved by doping the two sides of the semiconductor differently. Doping is the introduction of small concentrations of atoms with a different number of valence electrons than the base material into the crystal lattice. For example by doping silicon (4 valence electrons) with phosphorus (5 valence electrons) one additional electron is introduced into the crystal (n-type). Phosphorus is therefore called a donor and it creates energy states in the energy gap very close to the conduction band. This effectively moves the Fermi level very close to the conduction band edge. From here the additional electron can be excited easily into a conducting state. Depending on the concentration of donors the energetic distance between the Fermi level and the conduction band edge can vary. Doping with an atom with only 3 valence electrons (acceptor) causes an energy state close to the valence band. This energy state accepts low energy electrons and thereby forms holes in the valence band (p-type). Correspondingly the Fermi level in p-type material is close to the valence band.

By joining n-type and p-type materials (pn-junction) the Fermi levels align causing electrons from the n-side to move to the p-side (vice versa for the holes) which creates the required electrochemical potential across a region depleted of charge carriers (space charge region). The accumulation of opposite charge carriers on both sides of the depletion region forms an internal electric field which limits the diffusion of charge carriers from high concentration sites to low concentration sites. The pn-junction is in dynamic equilibrium when the electrochemical potential (combination of the electric potential and the chemical potential, i.e. potential caused by the charge carrier concentrations) is flat and has no gradient therefore no current arises. Mathematically speaking one could say that the diffusion current (caused by the concentration gradient) exactly cancels the opposite drift current (caused by the internal field), however, this does not describe reality correctly as both potentials effect the same particles. Figure 3.2 illustrates the conditions around the space charge region. Appreciate how the diffusion of charges creates the electrical field which manifests in a built-in voltage U_{bi}.

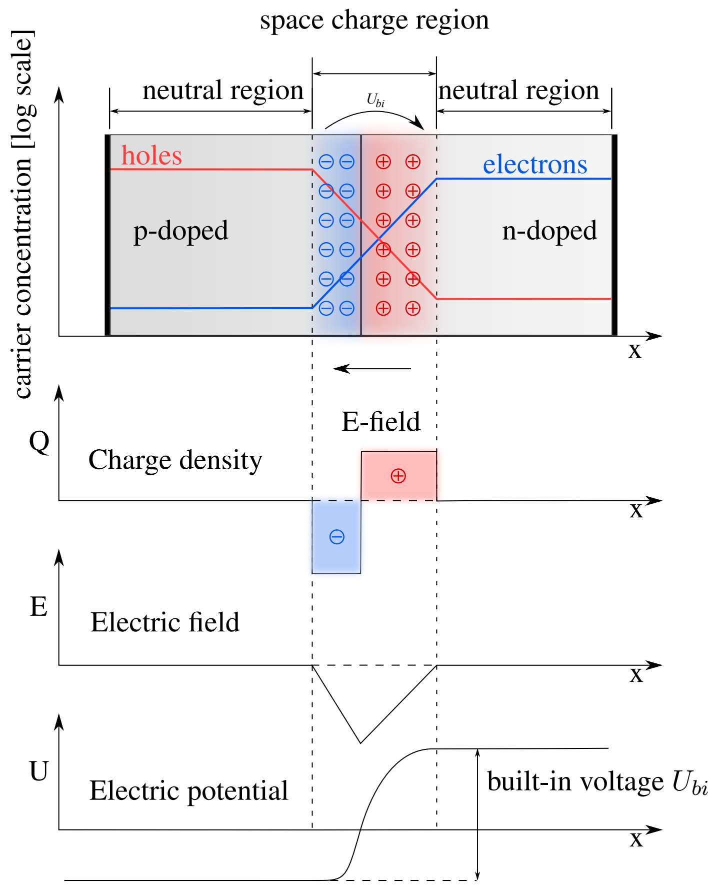


Figure 3.2: p-n junction in equilibrium, with zero external voltage bias. Below, plots for charge density, electric field and voltage. [2]

Upon applying a voltage bias U on the pn-junction the diffusion barrier is modified resulting in net currents I which can be described by the diode or SHOCKLEY equation

$$I(U) = I_{ph} - I_0(e^{qU/kT} - 1) \tag{3.1}$$

with the saturation current I_0, elementary charge q, BOLTZMANN constant k and photocurrent I_{ph}. Obviously in the dark I_{ph} must be zero, however under illumination excess charge carriers are generated which contribute a constant offset to the current. Under 'forward' bias ($U > 0$) the internal field is reduced and therefore the diffusion enhanced. Electrons will travel to the n-side and holes to the p-side which is effectively a separation of charge carriers which result in the current. Under 'reverse' bias ($U < 0$) the diffusion barrier is increased and charge carrier separation inhibited even more, the contribution from the drift is slightly larger causing a small negative current, however increasing the reverse bias does not further increase the drift current. This rectifying (diode) behavior is shown in the characteristic in Fig. 3.3.

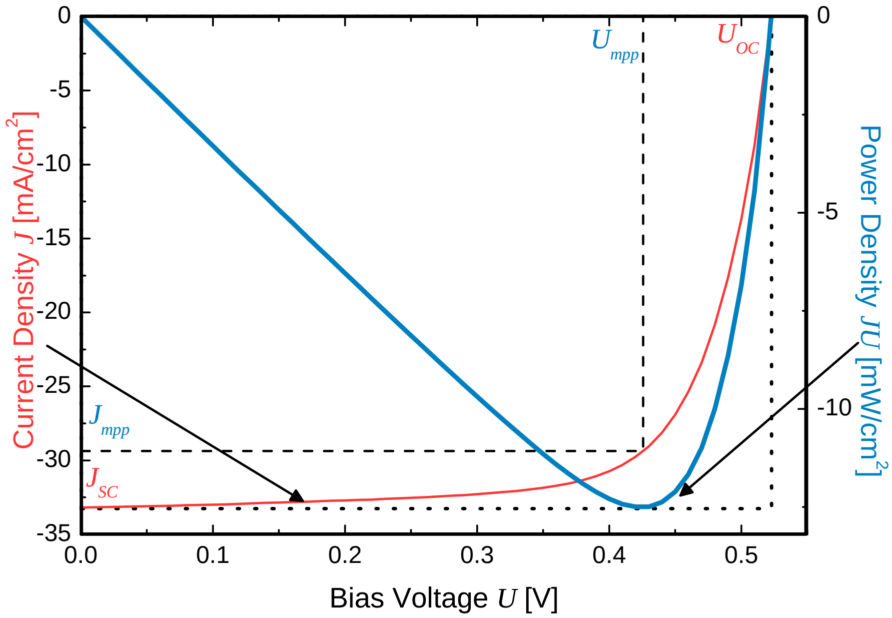


Figure 3.3: Typical $J(U)$ characteristic of a solar cell

Notice the following aspects about Fig. 3.3. Instead of the current I the solar cell characteristic is given in terms of the current density $J = I/A$. This expression normalized to the cell area A is common in research literature since here the specific area of the device is not as relevant as in system sizing. Furthermore the characteristic is mirrored across the voltage axis. This is also very common in research literature as here usually the physical current direction is the convention as opposed to the technical current direction which is much more common in engineering.

The voltage at the terminals of the solar cell in the open circuit is U_{oc} while the current in short circuit is I_{sc}. According to the KIRCHHOFF rules when connecting a load with resistance R_L to the solar cell, the voltage drop across the resistance and the voltage generation by the PV cell match up. This is also true for the current flowing through both devices. This so-called operation point can be determined graphically from the intersection of the solar generator characteristic and the load characteristic (see Fig. 3.5). The power $P = IU$ provided by the solar cell to the load is given by the rectangle under the the $I(U)$ characteristics with the corners in the origin and the operation point. At a specific operation point the power maximizes (maximum power point, mpp) which is the power value P_{mpp} used for the calculation of the efficiency of the solar cell.

The $I(U)$ characteristic of PV power generation depends on the temperature and illumination spectrum as well as intensity (compare Eq. 3.1). As a consequence the maximum power point and by extension the efficiency depend on these environmental parameters as well. Therefore standard test conditions for the determination of the nominal efficiency have been established to allow the comparison between different solar cells:

- device temperature 25 °C
- illumination intensity 1000 W/m^2
- illumination spectrum AM1.5g

However, Eq. 3.1 describes just the ideal case. In reality further loss mechanisms distort the $I(U)$ chacteristic requiring a more complex model description. An improved model is given by

$$I = I_{ph} - I_0(e^{q(U+IR_s)/mkT} - 1) - \frac{U + IR_s}{R_{sh}} \tag{3.2}$$

with the ideality factor m, series resistance R_s and shunt resistance R_{sh}. The ideality factor is typically a number between 1 and 2 and changes with the dominating recombination mechanism of the charge carriers. The series resistance can be caused by a bad contact between electrode and semiconductor or the semiconductor layers. The shunt resistance might be caused by parasitic currents across grain boundaries of the semiconductor material. The equivalent circuit of the non ideal solar cell described by Eq. 3.2 is shown in Fig. 3.4a. The effect of the parasitic resistances on the $I(U)$ characteristics is shown in Fig. 3.4b,c.

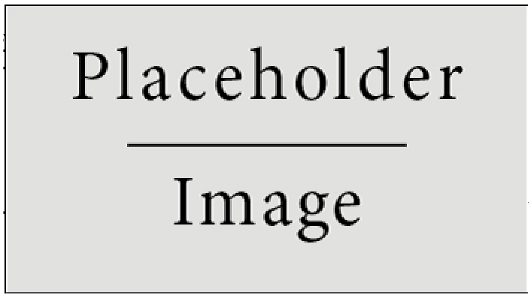


Figure 3.4: (a) Equivalent circuit of a solar cell including parasitic resistance. Also shown are the influence of the series resistance (b) and the shunt resistance (c) on the solar characteristics. (Source: [3])

The distortion caused by the dark current losses as well as the parasitic resistances is summarized in the fill factor FF which is a measure for the squareness of the $I(U)$ characteristics and is especially useful in comparing different devices of the same type. The efficiency η under illumination intensity G can thus be expressed by:

$$\eta = \frac{P_{mpp}}{GA} = \frac{I_{sc}U_{oc}FF}{GA} \tag{3.3}$$

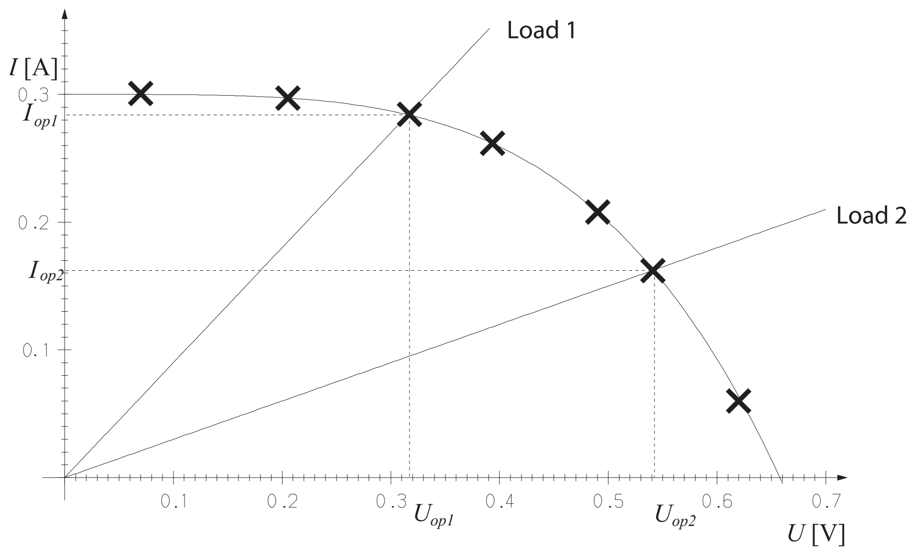


Figure 3.5: Operation points of a solar generator with different loads.

- Can you rearrange Eq. 3.1 to give $U_{oc}(T, I_{ph})$?
- Considering that $I_{ph} = I_{sc}$ can you determine m and I_0 from measurements at different G?
- Can you determine m and I_0 from measurements in the dark?
- Can you determine R_s and R_{sh} from the $I(U)$ characteristic in the dark? How?
- Can you describe qualitatively how I_{sc} might be dependent on temperature and illumination.

3.3 Experimental setup

3.3.1 Measurement strategy

A simple method to determine a solar cell characteristic is suggested by Fig. 3.5: different loads (ohmic resistors) lead to different operation points.

- What is the basic requirement allowing for such a strategy?
- What is the difference between a (rectifying) diode, a photodiode, and a PV cell?
- Which part of the diode characteristics is drawn typically for a PV characteristics as in Fig. 3.5?

In this experiment we want to investigate the change of the solar cell $I(U)$ characteristic upon variation of the device temperature and illumination conditions. Therefore we need several components in our setup (see Fig. 3.6).

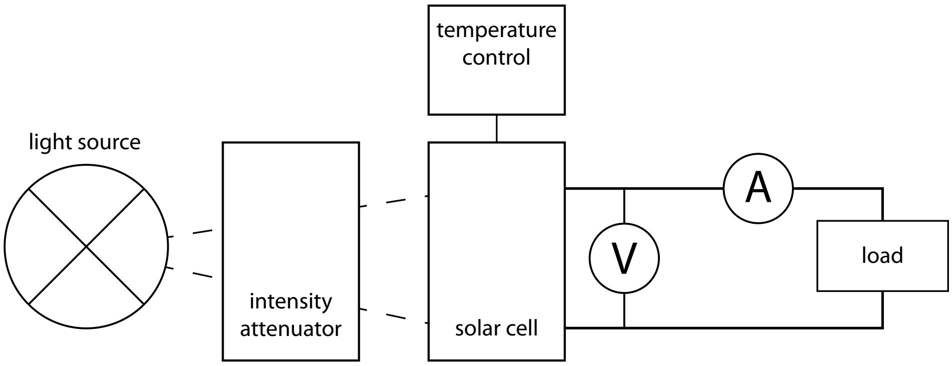


Figure 3.6: Sketch of the experiment to determine an operational point.

We need:

1. A light source to illuminate the solar cell
2. Some device to change the intensity of the illumination
3. The solar cell
4. Some device to control the temperature of the solar cell
5. Several loads to access different operation points (compare Fig. 3.5)
6. Measurement devices to record the electrical parameters of the system

3.3.2 Light source

Ideally the spectrum of the light source should be as close to the solar spectrum as possible to obtain reliable results. In professional laboratories the solar spectrum is approximated with complex apparatuses (Solar Simulator) and expensive combinations of lamps and filters, however, our experimental setup consists only of a set of special halogen lamps. Notice, that as semiconductors only absorb parts of the spectrum due to their band gap their performance depends on the specific spectrum.

The solar spectrum has notable dips which arise from the absorption by water molecules in the atmosphere. Therefore a water filter is positioned in front of the lamp to simulate this behavior.

With the help of the **pyranometer** the right positions of the solar cell corresponding to the chosen irradiation values can be found. Note that the light intensity is rather inhomogeneous close to the lamp! A device is available to investigate the homogeneity of the light field – if you want to quantify this.

The pyranometer has an output voltage proportional to the incident radiation. Its magnitude is roughly about $10\ \mathrm{mV}$ at $1000\ \mathrm{W/m^2}$. The pyranometer needs a time of about 20 s to adjust to a change in intensity! *For exact values see sensitivity specification on the pyranometer*. The calibration factor of the pyranometer is given on a small label on the instrument itself.

STOP **Attention:**
The pyranometer must not be exposed to radiation with intensity values of more than 1500 W/m^2!

3.3.3 Illumination attenuator

As we need to change the illumination intensity for parts of the experiment some methods to achieve this are possible.

1. Changing the power of the lamp: This method is impractical as lamps might require up to half an hour to stabilize. Changing the intensity this way also might change the illumination spectrum (different temperature) which would cause the semiconductor material to react differently. Furthermore this could also damage the lamp therefore it is preferable to set the lamp once for the experiment.
2. The light intensity decreases as a function of distance, by positioning the solar cell at different distances different intensities could be set. This requires a large setup for lower intensities and careful setting for the higher intensities.
3. Neutral density filters of different strength could be placed between the solar cell and the light source. They are expensive and require an additional device.

In our experiment we change the intensity by changing the distance to the lamp. A pyranometer to determine the radiation at a certain distance is provided, see Fig. 3.7. The pyranometer must be placed exactly at the same distance from the lamp as the PV cells, to make sure that the radiation is the same. Please, handle the pyranometer with great care!

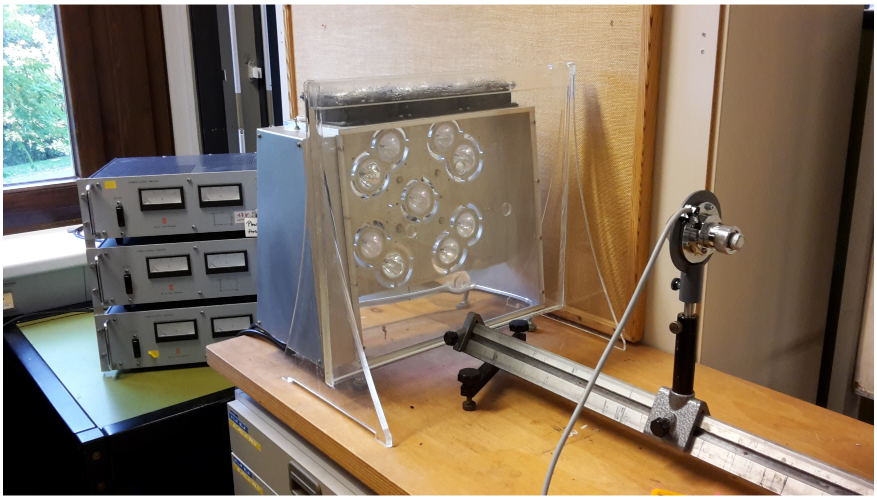


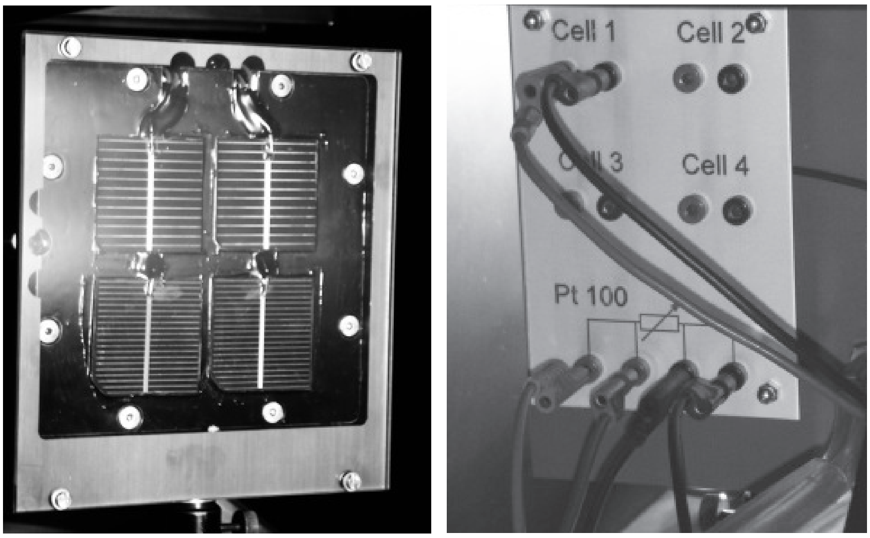
Figure 3.7: Solar Simulator with pyranometer

3.3.4 Solar cell

Various housings with one or several solar cells (see Fig. 3.8(a) for an example) can be mounted on an optical bench. Several sample holders with either crystalline (c-Si), polycrystalline (pc-Si) or amorphous (a-Si) solar cells are provided. Each mount has cells of just one type. The crystalline holder has four cells, where the two cells on the top differ from the two cells at the bottom only in their antireflective coating. Comparison of the $I(U)$ curves of different cells when changing conditions (radiation, incidence angle etc.) will be interesting.

The mount for the solar cells contains connectors for several purposes (Fig. 3.8(b)):

- electric connectors for voltage and current measurements,
- four-wire connections for a Pt-100 sensor, which is inside the mount, and
- tube connectors for heating/cooling liquid (connected to a thermostat).



(a) (b)

Figure 3.8: Crystalline PV cell mount (a) front view (b) back view with electrical connections

3.3.5 Temperature control

As the efficiency of the PV cell depends on temperature, the temperature of the device needs to be set to a fixed value. This is especially challenging as illuminating the solar cell will heat it tremendously. Different options are thinkable, for example Peltier elements or water cooling. Our sample holders will use the latter option and can be connected via tubes at the back of the cell housing to a thermostat water bath (see Fig. 3.9(a)).

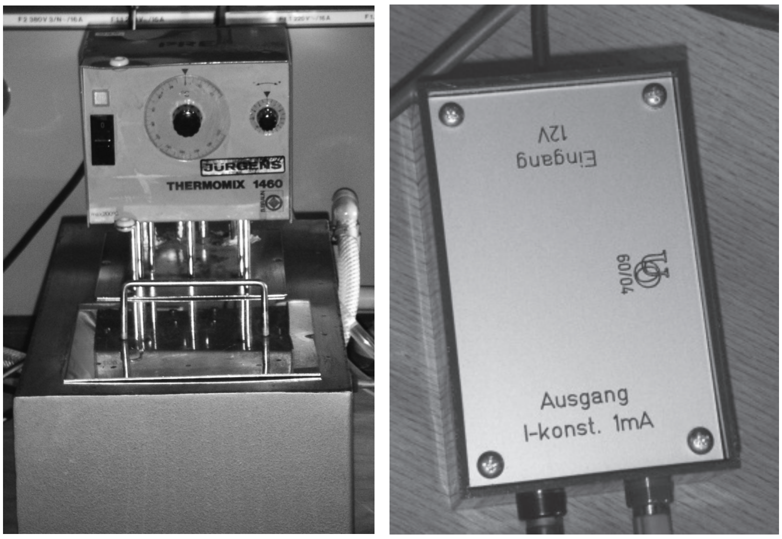
The water level in the thermostat has to cover the heater coils completely. The cell temperature is taken from the Pt-100 readings, NOT the thermostat! (A constant current source similar to the one shown in Fig. 3.9(b) shall be used. It provides a small current which results in negligible influence on the temperature measurement.)

3.3.6 Loads

A **Resistor** box is provided for varying the load R, see Fig. 3.10. When you vary R, take care that your data points cover the whole **voltage range** *with roughly constant steps*. (Sketch of data!)

3.3.7 Measurement circuitry

In order to obtain your measurement data you may use the simple circuitry from Fig. 3.6. Use 2 multimeters as voltmeter and amperemeter (voltmeter with a shunt for improved accuracy) and connect various load resistors one after another to change your operation point.



(a) (b)

Figure 3.9: (a) Thermostat used to control PV cell temperature (b) Constant current source for Pt-100

3.3.8 One-Diode Model

The second part of the experiment is a hardware simulation of a PV cell (here: a one-diode model).

- What electric components do you know of?
- Why a diode?
- What role do resistors play?

Set up the one-diode model box as an ideal solar cell. Ideal means the series resistance is zero and the shunt (or parallel) resistance is infinite.

- How do you realize an infinite resistance?
- How do you get close to zero resistance for the load? (How close?)

For the experiments with the model we currently have 3 different diodes, representing 3 different materials for PV cells (datasheets should be available with the setup or ask your supervisor):

- 1 N 5408 (std. Si rectifier)
- SR 560 (Schottky diode)
- AA 119 (Ge low current diode)

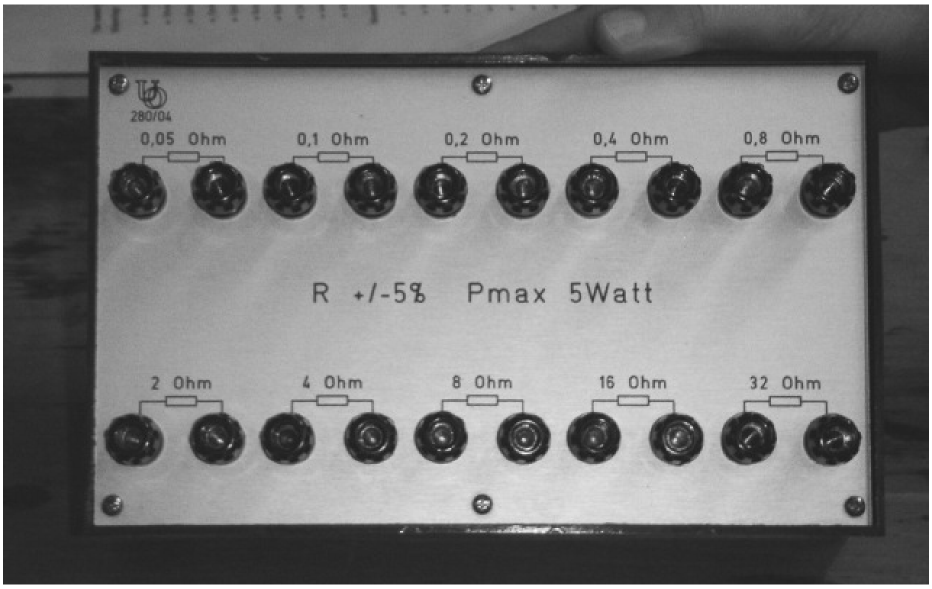


Figure 3.10: Resistor box as variable load.

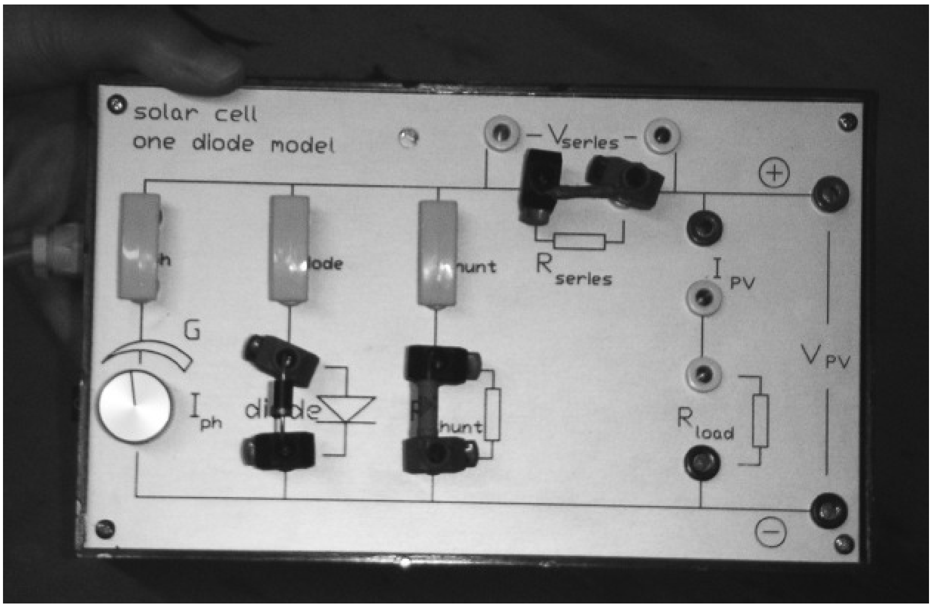


Figure 3.11: One diode model to represent a PV cell.

3.4 Tasks

3.4.1 Interview Questions

After your preparation you should be able to answer the following questions:

1. Explain the model of energy bands and the difference between metals and semiconductors.
2. Explain the terms conduction band, valence band, energy gap.
3. What is doping?
4. How do the energy bands behave at a p-n junction?
5. Explain diodes and photodiodes
6. Give the SHOCKLEY equation, explain the variables.
7. What is the temperature dependency of the open circuit voltage
8. Draw the equivalent circuit of the solar cell (one-diode model)
9. Be able to explain the important parameters of photovoltaic cells
10. What is the meaning of the ideality factor?
11. How can these parameters be determined from the $I(U)$ characteristics
12. What are the standard test conditions?
13. How is solar radiation measured (pyranometer)?
14. How can current be measured using a shunt resistor
15. Describe the main components of the experimental setup.
16. Describe the main tasks of the experiment.
17. Which safety precautions are required while performing the experiment?

3.4.2 Experiments

According to the previous discussion the efficiency of a photovoltaic device depends mainly on cell temperature and on incident radiation. The aim of this experiment is to see the influence on a single solar cells. In order to distinguish the effects, the parameters are usually investigated separately in Physics, i.e. one parameter is varied while the others are kept constant.

Please consider that every current measuring device has some internal resistance. So the measurement of the 'real' short-circuit current might require a shunt resistor with a very small resistance.

Current and voltage in the circuit according to Fig. 3.6 are measured with multimeters for various resistive loads R. The resulting diagram would look like the one shown in Fig. 3.5.

- Does the suggested voltage corrected measurement of the PV cell lead to smaller error bars? Consider an internal resistance of the ammeter of 200 Ω and a 10 $\mathrm{m}\Omega$ shunt. (Later at evaluation, obviously, use your experimental data.)
- Under the same conditions with the same load resistor R but changing the ammeter (internal resistance/shunt): Into which direction will your measurement points shift, in a diagram as Fig. 3.5? (What happens if you have chosen a current correct circuit?)

3.4.3 Warm-up

Task 3.1 — Calibration

It might prove useful to establish the radiation distribution along the optical bench, $G(x)$, prior to running the various series of experiments. The calibration factor should be given on a label on the pyranometer itself; calculate the maximum voltage the pyranometer may receive! (This could be done during temperature equilibration of the thermostat bath to use time efficiently.)

Your work in the lab will be more easy when you prepare your measurement tables beforehand. Design such tables in a way that you can also do all calculations without effort (and have sufficient space for remarks and observations).

Task 3.2 — Test measurement

Make a first rough measurement of the characteristics of one solar cell with the measuring circuit of Fig. 3.6. Compare your results qualitatively with the graph shown in Fig. 3.5. (If this works properly, proceed by using load resistors with resistance values in between to increase your resolution.)

Task 3.3 — Illumination and temperature dependency of solar cells

- Record the $I(U)$ characteristics for five different levels of radiation at constant temperature (i.e. $25\ °C$). – Steps of 100, 200, 400, 600, 800 W/m^2 might be a good choice.
- Take the characteristics for 3 additional temperatures at one moderate illumination (e.g. 400 W/m^2). – Reasonable settings would be 35, 45 and 55 $°C$.

Task 3.4 — (Optional) Solar cell types

Determine at least the characteristics for one other cell type.

3.4.4 Evaluation and report

The characteristics of each cell should be plotted in one diagram (i.e. the $I(U)$ curves for different G at const. T and for different T at constant G)

Task 3.5 — Temperature and illumination dependency of solar cell parameters

- Use the plots of the cell characteristics to determine the short circuit current and the open circuit voltage for each combination of temperature and irradiation (if necessary, extrapolate to zero voltage and zero current, respectively).
- Make diagrams of:
  - short circuit current versus temperature
  - short circuit current versus irradiation
  - open circuit voltage versus temperature
  - open circuit voltage versus irradiation

  and discuss the dependencies.

Task 3.6 — (Optional) Variation of solar cell parameters in different types

- Compare the characteristics of the cells of different materials.
- What are the most obvious differences among them?

Task 3.7 — (Optional, advanced) Fitting solar cell characteristics

- Try fitting your measurement data to the one-diode model. What are the fitting parameters?
- Do the resulting curves correspond with expectations derived from 'theory'? (Which is true: measurement or 'theory'?)

Task 3.8 — Power characteristic of solar cells

Calculate and draw the power output into the $I(U)$ diagram of (at least) one solar cell.

Determine the efficiency of (at least) one solar cell. That is, find the maximum power point and calculate the ratio electric power output/irradiated power on active cell area and plot it versus

- temperature,
- irradiation.

How does the PV cell efficiency change with temperature and irradiation?

3.4.5 One-Diode Model

Task 3.9 — Ideal equivalent circuit

1. Tune the G-dial, i.e. the current source, to some arbitrary level. Connect four multimeters to measure:
   - the current from the current source (I_{ph} equivalent to the level of illumination)
   - the current through the diode (I_{diode})
   - the output current of the model (I_{PV})
   - the output voltage of the model (U_{PV})
2. For the time being we shall measure the currents directly with multimeters, even though a conversion to voltages via shunts would be more accurate. Connect varying loads to R_L and note for each load the readings of all four multimeters. Include the two extreme points: zero load (short circuit) and infinite load (open circuit).
3. Make a plot of all three currents versus voltage.
4. How is the output current I_{PV} related to I_{ph} and I_{diode}? Give an equation relating the three currents.
5. Is there a similarity of the I_{PV} versus U_{PV} graph to your previous $I(U)$ graphs from real solar cells? How do you interpret the similarity?

Task 3.10 — Influence of parasitic resistances

The experimental goal with the one-diode model is to study the influence of series and shunt resistances on the current-voltage output. In the following, measure only I_{PV} and U_{PV}. Close the connections provided for the measurement of I_{ph} and I_{diode} with the appropriate connection pieces. Vary one parameter, while the other is kept at its ideal value.

1. For $R_{sh} = \infty$ measure three $I(U)$ graphs with
   - $R_s = 0.3\,\Omega$
   - $R_s = 0.9\,\Omega$
   - $R_s = 1.2\,\Omega$
2. For $R_s = 0$ measure three $I(U)$ graphs with
   - $R_{sh} = 175\,\Omega$
   - $R_{sh} = 33\,\Omega$
   - $R_{sh} = 15\,\Omega$

What is the visual footprint of a series resistance and a shunt resistance, respectively? Could you tell by looking at an $I(U)$ graph what the series and shunt resistances are?

Train your eye to see series and shunt resistances in $I(U)$ curves! (If you need help with that during experiment, ask your supervisor for assistance.)

Task 3.11 — (Optional) Non-ideality parameters in real $I(U)$ characteristics

- Go back to your solar cell data and choose one $I(U)$ curve. For this curve, calculate the series and shunt resistance by the method just developed. Purely visually, which resistance has left the larger footprint?
- Familiarize yourself with one more parameter, the fill factor. The fill factor is the ratio of maximum power over the product of short-circuit current times open-circuit voltage. Calculate the fill factor for all one-diode-model curves. Also calculate the fill factor for the curve from the real solar cells. What is the best match between one-diode-model and real solar cell?

Task 3.12 — (Optional) Saturation density current and ideality factor

Determine I_0 and m using both the illuminated and the dark method. Compare!

Ask your supervisor for the procedure.

Task 3.13 — (Optional) Series/parallel connection of solar cells

- Using either multiple diode model boxes or solar cells from one type connect the cells either in series and in parallel.
- In each case partially or totally shade one of the cells. How does the whole system behave?

Task 3.14 — (Advanced Optional) Spectral response and reflection

- For the very advanced and interested student you might ask your supervisor to visit their labs in order to measure the spectral response of the solar cell.
- Multiplying and integrating this with the solar spectrum and the spectrum of the lamp gives the short circuit current density. (Ask the supervisor for details) Is there a difference between both light sources?
- Measure the reflections of two cells with and without the anti-reflective coating. Compare!

3.5 Literature

3.5.1 References

[1] P. Kuiper. Sept. 2013. URL: http://en.wikipedia.org/wiki/File:Isolator-metal.svg.

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3.5.2 Additional reading

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♪♫ *Let the sunshine in*. Hair
. URL: http://www.youtube.com/watch?v=klObyJY1W_I.

4 — Liquid-Cooled Solar Collector

Practical application to harvest the solar energy

Learning objectives

After this experiment you will be able to

- use a solar simulator for measurements under laboratory conditions
- measure heat flow, small differences in temperature and irradiance
- measure the thermal properties of the solar collector
- determine, interpret and discuss the collector characteristics

4.1 Introduction

In chapter 2 we have learned about the nature of radiation which is the medium of energy transfer between the Sun and the Earth. The most important and relevant effect of the solar radiation is heating up the planet. Heat from solar radiation is the most ancient form of renewable energies which have been utilized by human beings (beside eating food of course). For example standing in the sunlight feels comfortable and sufficient solar heat can already be used to initiate various important processes like drying or even baking.

However, in the environmental conditions present on the surface of our planet radiation is not the only mode of heat transport. When discussing heat transfer in real life situations conduction and convection are further important mechanisms of heat transfer. We will need to understand all three modes in this experiment with a liquid cooled solar thermal collector. Heat from a radiation source is absorbed by the absorbing material of a solar collector. From the absorbing material the heat is transferred by conduction to a liquid. Within the collector the liquid moves and thus transports the heat from the absorbing region to a heat reservoir. The utilization of a glass panel in front of the collector reduces heat loss by convection and can thus improve its ability to convert irradiance into usable heat. The efficiency of this conversion – i. e. the fraction of irradiative power in the collector plane that can be utilized as heat – depends on both the level of irradiance and the temperature of the absorber.

The aim of this experiment is to determine the efficiency function for a simple solar collector for various temperature and irradiance conditions.

4.2 Physical principles

4.2.1 Heat transfer mechanisms

Thermal radiation is discussed in more detail in chapter 2 as black body radiation. To summarize, any black body object of temperature T emits the characteristic spectrum described by PLANCK's law as electromagnetic radiation. This is the only heat transfer which can pass a vacuum and is therefore the relevant mechanism for the energy transfer between the Sun and Earth. The heat transfer $\dot{Q}$ between two surfaces A_1 and A_2 with temperatures T_1 and T_2 is described as follows. Consider that surface A_2 receives heat only by the radiation from A_1. Furthermore A_2 emits radiation according to its own temperature towards A_1. Thus the net heat transfer with respect to surface A_2 can be described with the help of the STEFAN-BOLTZMANN law (Eq. 2.9):

$$\dot{Q} = \sigma A_1 F_{1\to 2}(T_1^4 - T_2^4) \tag{4.1}$$

The form factor $F_{1\to 2}$ accounts for the shapes and geometry of the two surfaces. σ is the STEFAN-BOLTZMANN constant introduced in chapter 2.

Heat conduction is the transfer of heat energy by diffusion along a temperature gradient. Basically the diffusion is a statistical process with the end result of equal temperature in the whole object.

Microscopically speaking, particles collide with each other and exchange kinetic and potential energy. It takes place in solids, liquids, gases and plasmas. The heat transfer $\dot{Q}$ between positions x_1 and x_2 along an object of homogeneous material with cross-section A is given by

$$\dot{Q} = -kA\frac{1}{x_1 - x_2}(T_1 - T_2) \tag{4.2}$$

k denotes the thermal conductivity, T_1 and T_2 are the temperatures at locations x_1 resp. x_2.

Heat transfer by convection is the transfer of heat by the movement of fluids. If the movement only originates from the differences in temperature (differences in pressure) this is called natural convection as known for example from winds. If the movement is caused externally (e.g. by a pump) it is called forced convection. Convection is actually the combination of conduction and mass movement and the dominant mechanism in gases and liquids. The heat transfer $\dot{Q}$ between a surface A with temperature T to the ambient T_a is described by

$$\dot{Q} = hA(T - T_a) \tag{4.3}$$

h is called the heat transfer coefficient.

4.2.2 Energy balance of a solar collector

Figure 4.1 illustrates the energy balance of a collector under steady state conditions. Steady state conditions mean the change of **temperature** T over **time** t can be neglected: $\mathrm{d}T/\mathrm{d}t = 0$,

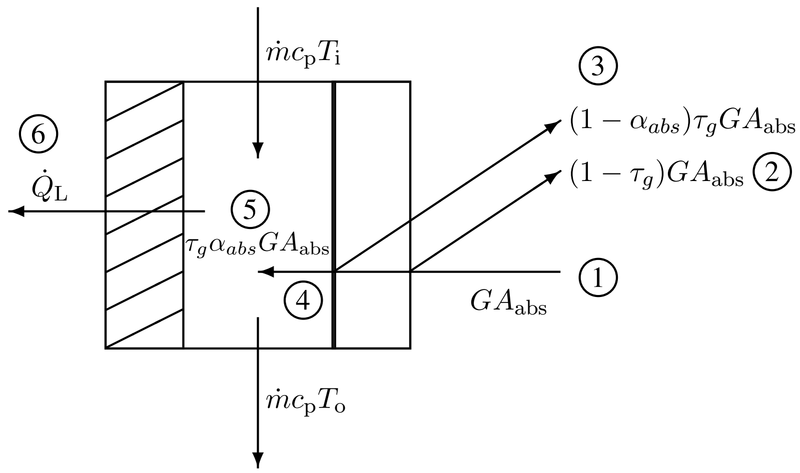


Figure 4.1: Energy Balance of a Liquid Cooled Solar Collector

Let us discuss the heat transfer processes step by step.

1. The incident energy (per second) amounts to the product of the absorber area A_abs times the radiation power density G.
2. Part of the radiation is reflected at the glass cover. Reflection r_g, transmission τ_g and absorption α_g relate according to: $\alpha_g + r_g + \tau_g = 1$. Assuming that the glass absorbs none of the

radiation (i.e. $\alpha = 0$) we can express the reflection of the glass r_g by $r_g = 1 - \tau_g$. Thus the energy lost by reflection is: $(1 - \tau_g)GA_{\mathrm{abs}}$

3. The absorber absorbs only a part of the radiation transmitted by the glass. According to its absorption factor α_{abs} such that the energy $(1 - \alpha_{abs})\tau_g GA_{\mathrm{abs}}$ is lost and only the energy $\tau_g\alpha_{abs}GA_{\mathrm{abs}}$ reaches absorber.
4. For simplicity we assume that all the absorbed heat is transferred into the working fluid.
5. Assuming a mass flow $\dot{m}$, a specific heat capacity c_{p}, and an inlet temperature T_{i}, part of the energy will be used to heat up the working fluid up to an outlet temperature T_{o}
6. A fraction of the heat entering the working fluid will be lost by means of all three heat transfer mechanisms. The combined heat loss by all mechanisms is summarized with the quantity $\dot{Q}_L$.

Considering all heat transfer into the fluid as positive and all heat transfer out of the fluid as negative the steady state energy balance with respect to the fluid becomes

$$0 = \dot{m}c_{\mathrm{p}}T_{\mathrm{i}} - \dot{m}c_{\mathrm{p}}T_{\mathrm{o}} - \dot{Q}_{\mathrm{L}} + \tau_g\alpha_g GA_{\mathrm{abs}} \tag{4.4}$$

4.2.3 Efficiency

Equations 4.1-4.3 are non-linear functions of temperature which results in a very complicated temperature behaviour of Q_L. However, we want to try a first order approximation. Every function can be approximated mathematically by a TAYLOR series (for more on the TAYLOR series refer to Ref. [1]). If the difference between the mean collector temperature $T_m = (T_{\mathrm{i}} + T_{\mathrm{o}})/2$ and the ambient temperature T_a is not too large the heat transfer process equations 4.1-4.3 can be described sufficiently well only with the linear term of their respective TAYLOR series and all higher order terms can be neglected. This allows us to summarize all loss mechanisms as the expression

$$\dot{Q}_{\mathrm{L}} = U_{\mathrm{L}}A_{\mathrm{abs}}(T_{\mathrm{m}} - T_{\mathrm{a}}) \tag{4.5}$$

where U_{L} designates the overall heat loss coefficient.

From the first law of thermodynamics the usable (or: consumed) heat flow $\dot{Q}_{\mathrm{u}}$ is defined as

$$\dot{Q}_{\mathrm{u}} = \dot{m}c_{\mathrm{p}}(T_{\mathrm{o}} - T_{\mathrm{i}}) \tag{4.6}$$

Except for the sign this expression is equivalent to the first two terms on the right side of Eq. 4.4. Together with the expression 4.5 we can rewrite Eq. 4.4 as:

$$\dot{Q}_{\mathrm{u}} = \tau_g\alpha_{abs}GA_{\mathrm{abs}} - U_{\mathrm{L}}A_{\mathrm{abs}}(T_{\mathrm{m}} - T_{\mathrm{a}}) \tag{4.7}$$

The efficiency η of the heat transfer into the fluid is defined as the ratio of the usable heat flow $\dot{Q}_{\mathrm{u}}$ obtained from the collector to the irradiance on the collector area GA_{abs}

$$\eta = \frac{\dot{Q}_{\mathrm{u}}}{A_{\mathrm{abs}} \cdot G} = \frac{\dot{m}c_{\mathrm{p}}\,(T_{\mathrm{o}} - T_{\mathrm{i}})}{A_{\mathrm{abs}} \cdot G} = \tau\alpha - U_{\mathrm{L}}\frac{(T_{\mathrm{m}} - T_{\mathrm{a}})}{G} \quad . \tag{4.8}$$

Hence, the collector efficiency η can be expressed as a linear function of the **irradiance related temperature difference** $(T_\mathrm{m} - T_\mathrm{a})/G$, as illustrated in the solar collector characteristics in Fig. 4.2. Sometimes the graph is given in terms of $T_\mathrm{m} - T_\mathrm{a}$ on the x-axis (i.e. not irradiance related); another possibility would be multiplying Eq. (4.8) with $A_\mathrm{abs} \cdot G$ resulting in the used heat $\dot{Q}_\mathrm{u}$ on the y-axis. Basically, all versions contain the same information.

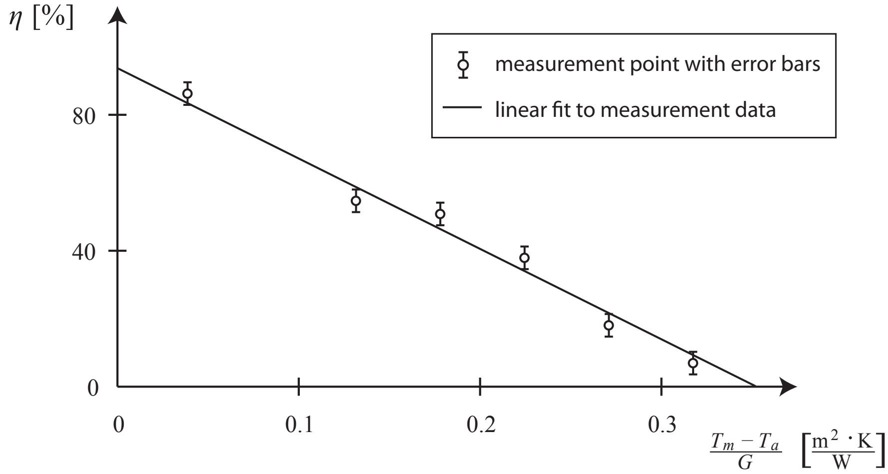


Figure 4.2: Solar collector characteristics $\eta = f(T_\mathrm{m} - T_\mathrm{a})/G$

- Why is it possibly not such a perfect theoretical model to assume an overall heat loss coefficient for all, conduction, convection, and radiation, losses?
- Can you imagine how experimental results may show that the model is not correct?

4.2.4 Understanding the collector characteristics

- All the experimental information for plotting the collector characteristics is contained in Eq. (4.8). Consider each term one by one and determine its role: Is it a universal constant, an experimental constant, an experimental parameter, or will it be a result of the evaluation?
  Naturally, the experimental values, both constants throughout the experiment (like the collector area) as well as variables (like the incident radiation) have to be measured, either once, or several times at particular experimental points.
- The experimental parameters will change during the course of the experiment. Which of them can be influenced directly and which only indirectly? For example, the collector outlet temperature T_o will rise when the inlet temperature is increased; surely, it will also vary with radiation. Which other parameters will alter T_o?
- In order to cover the full range of the collector function one has to produce several coordinate pairs, i.e. run through different values on the x- and y-axis. (What is actually denoted on the two axes?)

- Consider increasing G to modify the experimental conditions. In which direction of the x-axis will the operation point move? And in which on the y-axis? – What is your conclusion?
- Leaving the collector alone with no heat extracted by a consumer, the incoming radiation G will heat the circulating water until .... This means it is necessary to find which point in the diagram at equilibrium?
  Certainly, we do not want to wait for maximum $T_\mathrm{m} - T_\mathrm{a}$. Therefore what could be done?
  Nevertheless, during the experiment you might have to check at which point of the graph you have landed, in order to modify the parameters accordingly. **Do this during the lab!** Now you should be able to prepare a chart which you will use to record the data in order to create the diagram.

4.3 Experimental setup

4.3.1 Measurement strategy

In order to establish a collector diagram as in Fig. 4.2 and described by Eq. 4.8 the values of several physical quantities need to be known. This is the main part of the 'Collector Test Certificate'[1]. The area of the absorber can be measured beforehand and is constant over the course of the experiment.

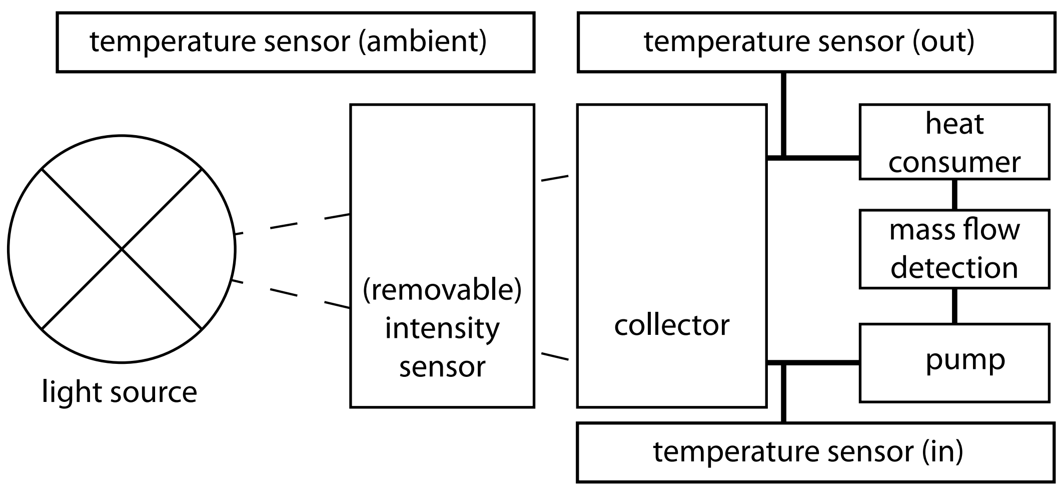


Figure 4.3: Schematic setup to record the collector characteristics

[1]Certificate of Collector parameters and its characteristics, determined under standardized procedure, see e.g. ([2, 3])

We need:

1. A light source simulating solar radiation
2. Some method to determine the light intensity G at the position of the collector
3. A temperature sensor to determine the ambient temperature T_{amb}
4. The solar thermal collector
5. Temperature sensors to determine T_i and T_o
6. Some means to measure the mass flow $\dot{m}$
7. Some means which consumes the collected heat
8. A pump to drive the mass flow

Solar Simulator

The solar simulator consists of four halogen floodlights rated 1000 W each shown in Fig. 4.4.

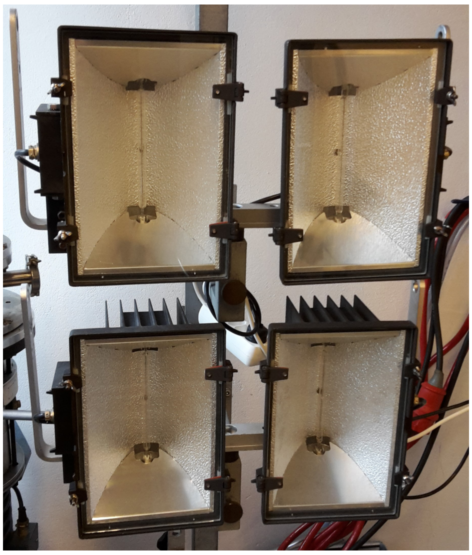


Figure 4.4: Solar Simulator

Temperature sensors

You have learned about several means to measure temperatures in the Introlab. In this experiment we use Pt-100 sensors. For the calculation of the temperatures T from the Pt-100 resistance readings R you may use the following function:

$$T = -244.037°\mathrm{C} + 2.3264\frac{°\mathrm{C}}{\Omega} \cdot R + 0.00113\frac{°\mathrm{C}}{\Omega^2} \cdot R^2 \quad (4.9)$$

Collector Test Setup

A detailed sketch of the experimental setup as it is used in our lab is shown in Fig. 4.5. The two main parts are the solar simulator and the thermal collector.

STOP The rack setup used in this experiment is not a commercial product. Thus the hardware is fragile and needs some special care.

The collector test setup is located on a movable rack (3), which allows the variation of the irradiance on the collector (11) by changing the distance from the light source. Water is used as the heat carrying fluid. The thermostat (5) controls the temperature of the working fluid and pumps the fluid to the head tank (7) which provides a constant static pressure for the collector. The surplus water returns to the thermostat by the overflow pipe (8). The remaining water runs to the collector through the inlet pipe (9).

After passing through the collector where the irradiance is absorbed and increases the temperature of the fluid, the water runs through the outlet pipe (13) and the flow control valve (14) to the weighing vessel (15). Here the mass flow is determined by measuring the time which is required to increase the mass of water in the vessel on the balance. During the determination of the mass flow the suction valve (16) is closed (i.e. the flexible pipe is taken out of the weighing vessel to interrupt suction). After the mass flow measurement, the suction valve (16) is opened and the vessel is emptied by the suction pump (20) of the thermostat. This closes the fluid circuit.

The thermostat unit allows the variation of the collector inlet temperature and hence the simulation of different operating conditions of the collector. A glass heat exchanger is mounted for additional cooling with the help of the laboratory cooling water system. It helps to stabilize the inlet temperature at 'lower' temperatures ($T_{\mathrm{in}} \leq 35\ \ ^\circ\mathrm{C}$). In conclusion, it is possible to vary the inlet temperature of the collector so that different values for the abscissa $(T_{\mathrm{m}} - T_{\mathrm{a}})/G$, can be used for the measurement of the corresponding collector efficiency.

- The setup contains a thermostat which tries to provide a constant water temperature. Which parameter in Eq. (4.8) is adjusted by this? (Possibly you have to see the setup or consult the sketch in Fig. 4.5.)
- We can simulate different heat loads by setting different temperatures at the thermostat. – How does a larger consumption effect the characteristic according to Eq. (4.8)? – A larger consumption means moving into which direction on the y-axis in the collector diagram.
  Sure, a maximal consumption means colder water is running into the collector and the average temperature of the collector not being much higher than the ambient as a result.

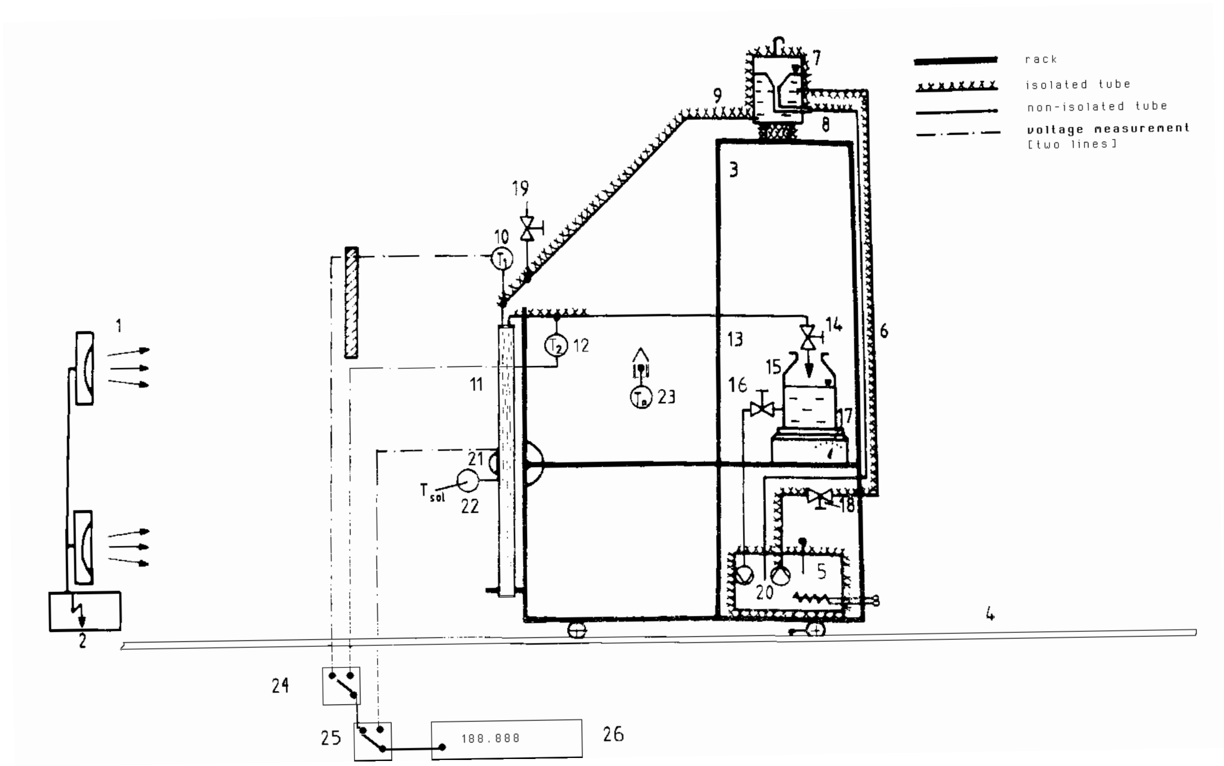


Figure 4.5: Schematic of the Collector Test Station

1. Solar simulator, 4 kW HMI-lamp
2. Power supply for lamp
3. Movable rack
4. Rail (obsolete)
5. Thermostat with electrical heating, cooling, and circulation pump
6. Flexible tube (10 mm diam.) with sponge rubber isolation (10 mm)
7. Constant head tank, insulated with glass wool (60 mm)
8. Overflow tube (20 mm diam.)
9. Collector inlet tube, isolated
10. Inlet temperature measurement, Pt-100
11. Solar thermal collector, with optional glass cover and optional transparent isolation
12. Outlet temperature measurement, Pt-100
13. Collector outlet tube, isolated
14. Flow control valve
15. Weighing vessel
16. Suction pipe from circulation pump
17. Electronic balance
18. Main cut-off valve (included in thermostat housing)
19. Vent valve (obsolete)
20. Circulation pump of thermostat
21. Movable Pyranometer resp. PV-Sensor
22. Pyranometer temperature measuring point, NiCr/Ni (obsolete)
23. Ambient temperature measurement house, Pt-100
24. Change-over switch $T_1 \longleftrightarrow T_2$
25. Change-over switch $T_1, T_2 \longleftrightarrow E$

*** 24./25. replaced by: multi-channel x-t recorder, with 1 mA constant power source for Pt-100s

26. Digital multimeter, range $0 - 200\mathrm{mV}$ and x-t recorder

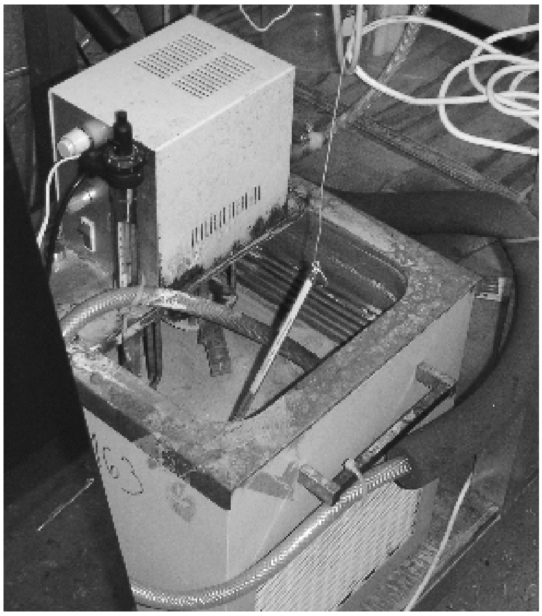
(a)  (b) 

Figure 4.6: (a) Water reservoir on top (b) Thermostat

- Which are the most common types of collector systems (classified according to circulation principle)?
- What would happen if the collector is left unattended for prolonged time? (While the solar simulator is on, no extra cooling is provided but a circulation pump is running.) Explain it in
  1. everyday language/concepts,
  2. how this shows in the collector equation (4.8), as well as
  3. what happens in the collector diagram (see Fig. 4.2).

4.4 Experimental Considerations

4.4.1 Removal of air bubbles

Air in the pipe and tube system impedes the heat transfer from the collector to the heat carrying media. This destabilizes the flow rate and may even disrupt the flow completely.

- It is not straightforward to check for air in the collector because you cannot look into it. But when the water circulates you can see if there are any air bubbles in the stream of water coming out of the collector by carefully observing the transparent parts of the piping system (e. g. glass heat exchanger). To extract the bubbles from the collector it seems advisable to increase the flow rate. This is done by connecting the suction pipe (which is usually inserted into the glass vessel on the balance) directly to the flow outlet (from where normally the water from the collector spills into the glass vessel on the balance. Ask your supervisor about the details!).

4.4.2 Flow Rate

- Think about a practical method to keep the flow rate constant in our experiment? Discuss with your supervisor beforehand.

A prerequisite for a constant situation is a stable flow rate through the collector.

- Very small mass flow ($\leq 5\mathrm{g/s}$) leads to bubbling in of air, thus $\dot{m}$ becoming unsteady.
- The mass flow should be adjusted with valve (14) so that $15\,\mathrm{K} > |\mathrm{T_o} - \mathrm{T_i}| > 5\,\mathrm{K}$.

4.4.3 Temperature Measurement

During the investigations small differences between T_i and T_o have to be determined accurately. Do the two Pt-100 sensors show the same resistance at the same temperature? There are two possibilities for checking the offset of the Pt-100s.

- Record their readings before light is absorbed by the system and before the water circulation is initiated. In this situation the Pt-100s should be in equilibrium with the ambient laboratory.
- When circulating the water WITHOUT heating (or cooling) the system one has the chance to remove any air bubbles which might sit next to a Pt-100 and produce a sub-climate. (This procedure has a drawback, which? See the x-t protocol of the preparatory step!)

With both methods you can see, whether the two (three) Pt-100 sensors actually display identical resistance values at the same water temperature.

- From which factor in the equation 4.9 does this mismatch arise?
- What is necessary to determine the offsets of the Pt-100s?

The measured difference in resistance resp. the calculated difference in temperature will have to be accounted for later, in all temperature measurements.

- The operation temperature T_i can be preset (coarsely) by the thermostat control; a counterflow heat exchanger (cooling water) supports stability in the lower T_i ranges.
- It is suggested to start with lowest temperature for T_i around $35\,°\mathrm{C}$).

The temperature equilibrium establishes by itself according to $\propto e^{-1/t}$. The **experimentalists** actually have to fashion stability! The additional heat exchanger allows fine tuning by altering the cooling water flow rate and thus control of heat extraction from the system. Some old lab hands also suggest slight shifts of the rack into the direction towards or away from the solar simulator to reach equilibrium between radiation input and heat extraction.[2]

[2] Credits to Martin Panusch.

4.4.4 Measurement Error Handling

Temperature

The interesting physical quantities are rarely measured directly. Therefore we have to consider the **propagation of errors** when we evaluate our measurement data and calculate the values of the physical quantities of interest. A simple example: When determining the flow rate of water through a tube the time period t_f and the mass m_f are measured. Using both values the mass flow rate is calculated as

$$\dot{m} = \frac{m_\mathrm{f}}{t_\mathrm{f}} \quad .$$

However, in reality, your measurements of mass and time have standard errors, which have to be determined by taking a series of measurements and then calculating the mean value and the standard error. How will these errors influence the standard error of the mass flow rate $\dot{m}$? Please, find out about the details of the propagation of errors and calculate the relative standard error of $\dot{m}$, if the relative standard errors of both t_f and m_f are 10%. (Actually, when measuring time with a stopwatch and mass with a balance, the error is rather an absolute.)

How does this mass flow, with its particular error, influence the results of the collector experiment? Obviously the final efficiencies η as well as the $(T_\mathrm{m} - T_\mathrm{a})/G$ values will have standard errors that depend on the accuracy of several measurements: temperatures, radiation level and flow rate. As this is rather complex for the moment you might concentrate on one item only: the effect of the flow rate on the accuracy of η as this includes an interesting catch.

- First establish the function for the propagation of the standard errors of the flow rate and the temperature measurement as they effect the error of η. (Keep other variables fixed, e.g. $\frac{\partial\eta}{\partial T_\mathrm{a}} = 0$.)

If the flow rate is increased, the temperature difference produced by the collector between inlet and outlet will decrease and vice versa. This can be understood by looking at two extreme cases:

- A flow rate close to zero will leave the collector with maximum temperature
- When the flow is tremendously fast there is no time for the liquid to gain temperature.

Therefore, only a certain amount of heat Q is transferred from the plate to the water. For simplicity one may assume that at constant conditions of radiation and inlet temperature the usable heat transfer $\dot{Q}_u$ is independent of flow rate and outlet temperature.

$$\dot{Q}_\mathrm{u} = const. = \dot{m}c_\mathrm{p}(T_\mathrm{o} - T_\mathrm{i}) \, .$$

With this assumption in the final error formula for η we can replace T_o by $\dot{m}$. Thus $\delta\eta$ will become a function of the flow rate only. The absolute/relative error margins of flow rate and temperature can remain in the equation, as they are considered constant.

- Now check: Does $\delta\eta(\dot{m})$ have a minimum?
- Discuss the influence of the mass flow $\dot{m}$ on the accuracy of the measured $\dot{m}\, c_p\, (T_\mathrm{o} - T_\mathrm{i})$ value!
- What is the consequence of these considerations for our experimental performance?

The effect should also be looked at experimentally:

- At constant conditions of radiation and collector inlet temperature, vary the flow rate between e. g. 5 and $25\ \mathrm{ml/s}$. Calculate the efficiency and its relative standard error by taking a series of measurements for each value of $\dot{m}$.

Radiation

For the purpose of characterization of a collector it is necessary to establish constant and reproducible conditions. Because of the high variability of the Sun real solar radiation is not a good light source for our purposes. In this in-door collector experiment we will use therefore a more defined radiation source which approximates a very specific and well defined standard solar spectrum. However, matching this standard spectrum exactly requires very expensive equipment which is why we only approximate the standard spectrum by using specific lamps. This has the consequence that we incorporate the imperfections of the solar simulator into the experiment: For example the radiation intensity varies to some extent over the area of the collector aperture. Please, consider the effects of inhomogeneous radiation on the accuracy of the experiment! Before reading on, first think on your own how the mean value of radiation intensity can be measured, if the value depends on the location x, y: ($G = f(x, y)$).

A way to handle this problem (in a rather easy and superficial way) is presented in the following:

1. Divide the collector aperture rectangle into four triangles (compare Fig. 4.7).
2. Measure the radiation intensity at the corner points of these triangles. On closer inspection you will find that you have to measure at five points – the four corners and the center of the collector area.
3. For each triangle the mean value of radiation is estimated to be the average of values measured at its three corner points. E. g. the left triangle (1–3–5) in Fig. 4.7 will receive an estimated radiation $G_{135} = (G_1 + G_3 + G_5)/3$.
4. The average of the collector area might be calculated in the same way from the value of the mean value of the four triangles: $\bar{G} = (G_{135} + G_{125} + G_{345} + G_{245})/4$. After some simplification (please check yourself!) this leads to

$$\bar{G} = (G_1 + G_2 + G_3 + G_4 + 2G_5)/6\ .$$

In this experiment the irradiance G is varied by varying the distance between the rack with the test stand and the lamps. Before you start measuring the thermal performance of the collector, you have to identify and mark positions of the collector, where the desired irradiance levels are prevalent.

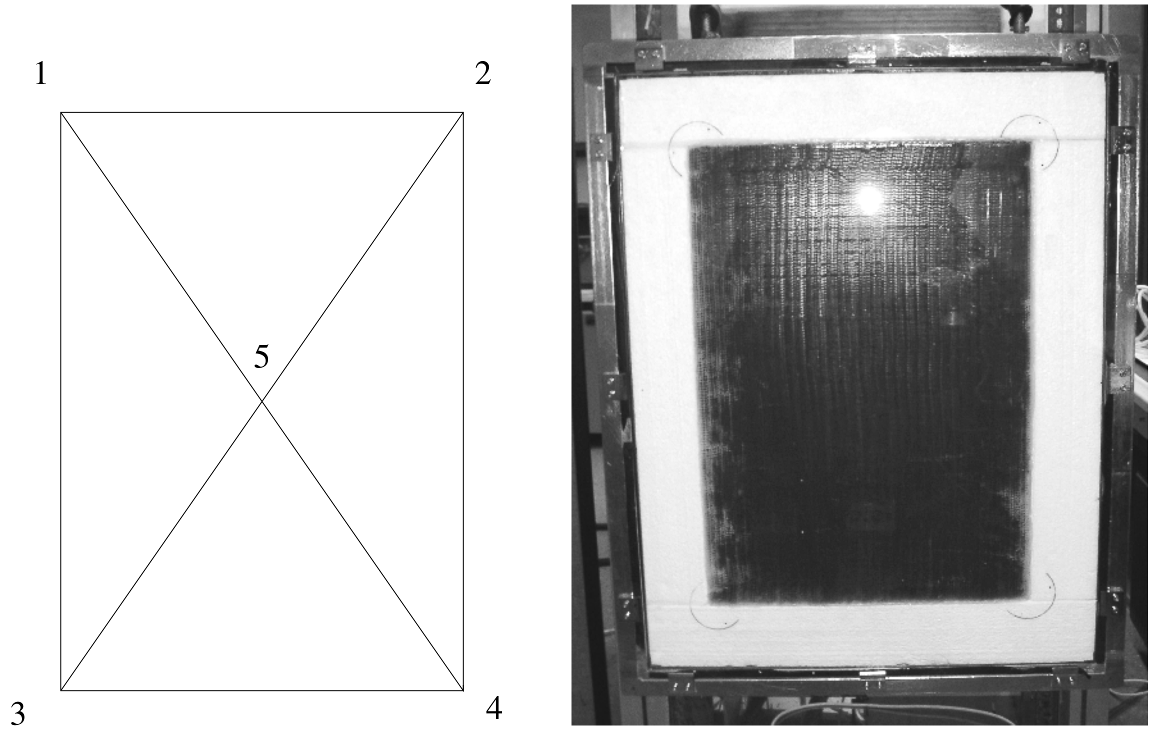


Figure 4.7: A Method to Estimate Radiation Mean Value

Note: According to the ISO EN 12975-2 norm (see Ref. [2]) the radiation in the collector plane has to be measured every 10 to 15 cm in each direction, horizontally and vertically. From those measurements the average has to be calculated (certainly, also a minimum standard deviation is required to judge the uniformity).

For sure, this procedure will get a more accurate mean radiation value. It takes only a bit longer to record these data, but will give you a good insight into the variation of the light across the collector surface.

4.5 Tasks

Interview Questions

After your preparation you should be able to answer the following questions or explain the given keywords:

1. Which heat transfer mechanisms do you know? Where do they occurr in the setup?
2. Which are the values to measure?
3. Which are the parameters accessible for change?
4. How do the parameters have to get modified in order to obtain data points all across the diagram?
5. Solar collector setup
6. Transparent insulating material, honeycomb
7. Heat capacity (esp. of water)
8. Energy balance equation
9. Resistance thermometer, Pt-100
10. Pyranometer, solarimeter
11. Statistical errors, Gaussian error progression
12. Describe the main components of the experimental setup.
13. Describe the main tasks of the experiment.
14. Which safety precautions are required while performing the experiment?

Measurements

Task 4.1 — Getting started

- Connect flexible cooling water pipes to lab cooling faucet (green, yellow, green) and the return faucet (gray).
- In order to operate and understand the collector setup properly you have to familiarize yourself with the various lines of flow. It seems useful to draw a sketch of the hydraulic system – which will go later into the report as a instructive part.
- To judge if equilibrium ($\mathrm{d}T_\mathrm{m}/\mathrm{d}t = 0$) has been established the 3 Pt-100s shall be monitored via an x-t recorder. A $1\,\mathrm{mA}$ constant current source for the Pt-100s, and the offset compensation of the x-t recorder should be used.
- A pyranometer is provided for measurement of the radiation at the collector surface.

Now you should be in a position to start and enjoy the investigations on the collector!

Task 4.2 — Operation[a]

- Get the Pt-100s connections ready and feed the voltage drop across them into the x-t recorder. Adjust the zero points. *A first measurement of the relative offset of the Pt-100s can be done now.*
- Switch on the pump of the thermostat to start circulation of the heat carrying liquid.
- Open the main valve (18) and wait until water returns via the overflow tube (8).
- Open the mass flow control valve (14) to the maximum.
  At this point it is best to remove air bubbles from the pipes and determine the offset of the Pt-100s a second time.
- Take the suction pipe into the weighting vessel to return water into the reservoir.
- Start the exhaust for the lamps (the switch is next to the entrance door of the lab). This is necessary as the lamps create a plasma arc which leads to a high fraction of ultraviolet light. This ionizes the air leading to formation of ozone which should be taken out of the lab.
- **These lamps are sensitive to on–off switching**.Therefore, they should be started only once during the course of the experiment in order to avoid fast aging of the bulbs.

[a] Several steps should actually be done together with the supervisor.

Task 4.3 — Characterization of the collector

- Measure the collector inlet and outlet temperature with the Pt-100s (see Ref. [4]) considering the occurence of systematic errors during the measurement of $(T_\mathrm{o} - T_\mathrm{i})$).
- Adjust until a steady state is reached $(\mathrm{d}T/\mathrm{d}t = 0)$. Check by observing $T_\mathrm{i}(t)$ and $T_\mathrm{o}(t)$ with the help of the x-t recorder.
- Note the final temperatures using a multimeter (in the case this gives a higher resolution than the x-t recorder).
- Measure the ambient temperature. (Either with a digital thermometer or a NiCr/Ni thermocouple sensor, or simply a mercury thermometer. For reference (see Ref. [2] and check where to measure the ambient temperature T_a).
- Measure the mass flow with a digital watch and balance. Determine the measurement uncertainty for each final mass flow value!
- Measure the irradiance with the solarimeter as discussed in section 4.4.4. (The radiation intensity can be preset by moving the rack; possibly start with highest irradiance $\approx 650\ \mathrm{W/m^2}$).
- For each thermostat setting perform measurements at $G = 0$. (Please, do not switch off lamps but cover the collector with something of proper size.)

- What can be gained from measurements at $G = 0$?
- How is the heat balance influenced in this case (refer to Eq. (4.8) & Eq. (4.4))?

The collector characteristics should be determined at about 12 operating points which are uniformly distributed over the curve. (For example at three different temperature levels of T_i and four different irradiation levels G).

As the graph is approximately known beforehand (see Fig. 4.2) one can predict the operation conditions: $(T_\mathrm{m} - T_\mathrm{a})/G$ must be set in order to receive a uniform distribution of the measuring points over the whole range. For example, the parameter set $T_\mathrm{m} = 80$ °C, $T_\mathrm{a} = 20$ °C and $G = 120$ W/m^2 results in $(T_\mathrm{m} - T_\mathrm{a})/G = 0.5\,\mathrm{Km}^2/\mathrm{W}$ and is therefore useless as this point is out of the range of the characteristics. Negative efficiencies will cause the collector to loose more heat than it receives from the 'sun'.

Task 4.4 — (Optional) Measurement with honeycomb structure

The measurement of the stationary collector characteristics can be done for several configurations. Which for example can be a honeycomb structure available in 2 different thicknesses which can be inserted into the collector. Also the operation with and without glass cover is possible. Fig. 4.8 shows a cross section of the collector with glass and the thick honeycomb inserted. Ask your supervisor if these options are available.

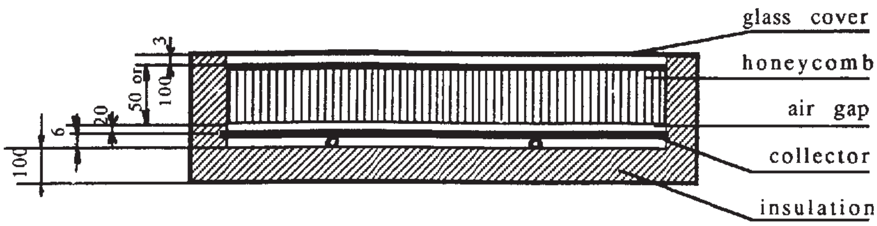


Figure 4.8: Cross-Section of the Collector

Task 4.5 — Shut-down procedure

- Close the flow control valve (14). (Short circuit circulation line.)
- **Close the main valve on the thermostat (18)!!!** Otherwise the water from the head tank will flood the laboratory!
- Switch off the thermostat, balance, x-t recorder, and multimeter(s).
- Close the tap of the cooling water. Sort back flexible pipes.
- Switch off the multi plug extension. Disconnect the Pt-100s, x-t recorder, and sort back the cables.
- Switch off the lamp power supplies (red square switches).
- Switch off the exhaust ventilation.

4.5.1 Evaluation and Report

Task 4.6 — Stationary collector characteristics

Display the stationary collector characteristics in a diagram $\eta = f((T_\mathrm{m} - T_\mathrm{a})/G)$, **with** error limits. For that, the measurements of $\dot{m}, T_\mathrm{a}, T_\mathrm{i}, T_\mathrm{o}$, G and A_abs have to have been taken.

The collector characteristics should approximately have the shape and range of Fig. 4.2. The error margins are a result of the errors in $\dot{m}, G$, the various T's, uncertainty in A_abs, and so on.

The record shall contain a 'collector test certificate' for the 'customer' who wants to 'buy' such a collector. It should highlight the 'benefits' of the transparent insulation, and the reduced 'losses' of the (glass) cover.

Task 4.7 — Parameters of the thermal collector

The effective optical efficiency and the overall heat loss coefficient are the main parameters to describe a collector's performance.

effective optical efficiency An estimate of $\alpha_{abs} \cdot \tau_g$ from the characteristics may be achieved by extrapolation of the linear efficiency function to $T_\mathrm{m} = T_\mathrm{a}$.

loss coefficient Theory assumes that all thermal losses can be described by a constant overall heat transfer coefficient U_L. However, U_L depends on temperature.
Use one (or several) methods to derive a value for the heat loss coefficient. In the case of various methods: Compare the results.
Is the linear model for the energy balance applicable in your situation?

Do not forget to *elucidate* the general meaning of both variables, *explain* your findings, and *explicate* the meaning of your specific values.

Task 4.8 — Additional questions

The following questions should be answered briefly in the report (possibly with a sketch):

- Which important systematical and statistical errors did occur?
- While measuring the mass flow during the experiment T_o usually increases drastically – please explain.
- What is the benefit of the selective surface used in this collector?

4.6 Literature

4.6.1 References

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♪♫ *Warm sun*. Ten years after

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