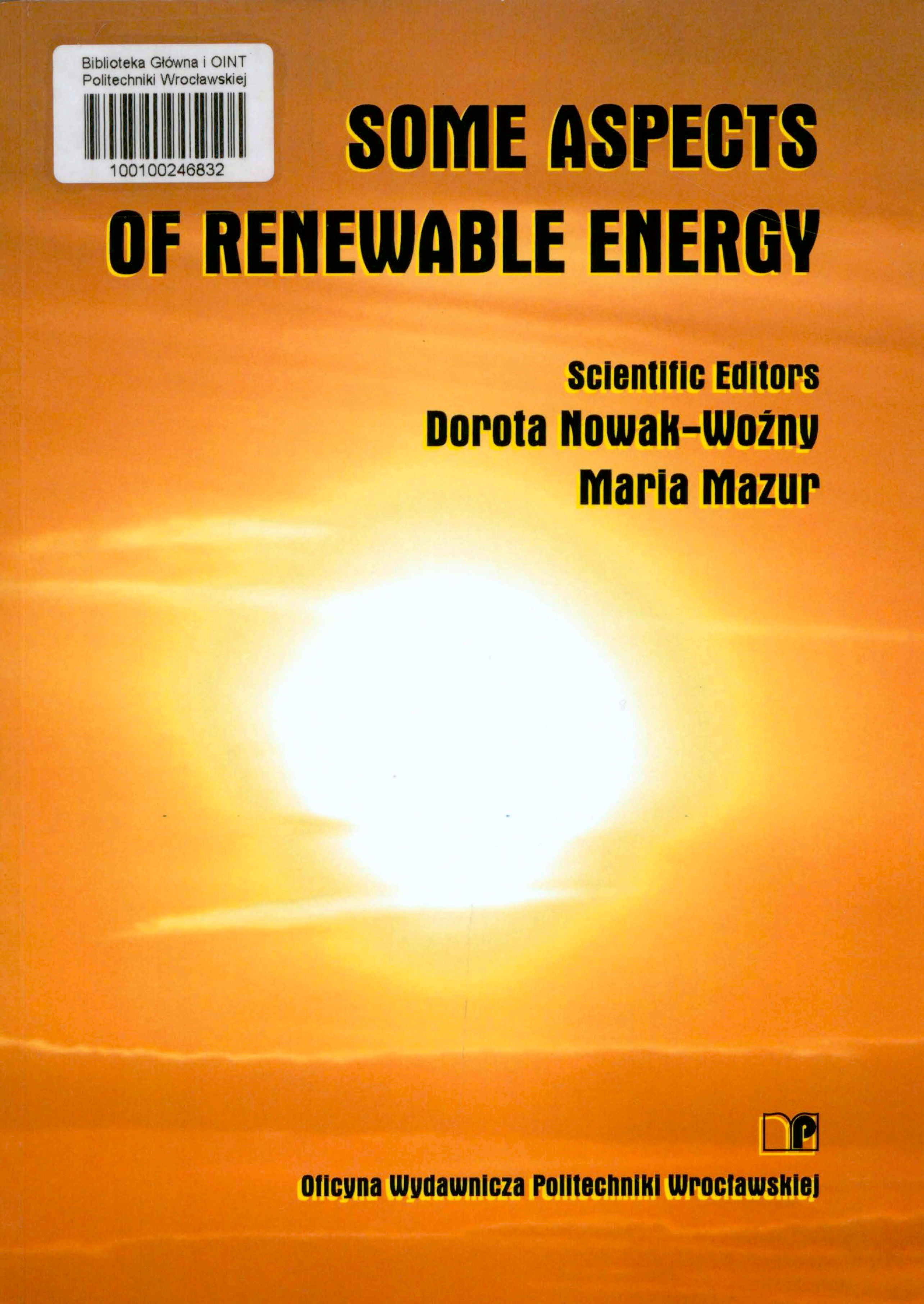

SOME ASPECTS OF RENEWABLE ENERGY

Scientific Editors
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Oficyna Wydawnicza Politechniki Wrocławskiej

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Contents

Preface

This publication is the result of cooperation in the field of renewable sources of energy among scientists from the Czech Republic, Slovakia and Poland.

The issue of the use of renewable sources of energy is vital with respect to the exhaustion of natural resources on the one hand, and rapid increase of the environmental pollution on the other hand.

The increasing environmental pollution (also greenhouse gasses) is currently a big problem – both economic and social. Due to that fact, on the one hand, new engineering solutions are being sought within current technologies, and, on the other hand, solutions which allow to acquire energy from renewable sources are being looked for. One must realize that increasing demand for energy contributes to overexploitation of natural resources, which leads us to an inevitable global economic crisis. In this situation countries which export natural resources for energy needs will take an opportunity to subordinate its receivers, both economically as well as politically. Due to that fact, actions of countries which might be the subject of such a manipulation should lead to an intense support of both progress in the field of creating new constructive solutions for traditional devices, as well as reaching for renewable sources of energy.

Chapter 1

The future of the energy power system

In this chapter we will tell about greenhouse effect, about some problems of the conventional power industry and about some interesting phenomenon that allow the direct conversion of the renewable energy into electricity.

In the system: Sun–(Earth-atmosphere)–Moon there is stored a large amount of renewable energy. But optimal usage of this energy is conditioned by the progress of the materials science (to obtain new materials) and by the government's energy power systems politic (to reduce the investment cost).

We hope that this text will be helpful for readers to understand how interesting and important can be the processes of renewable energy obtaining.

1.1. The greenhouse effect

The conventional energy power system generates air and water pollution. This effect is proportional to the growing demand of energy and has some influence on the greenhouse effect. The greenhouse effect is closely associated with the existence and the content of the Earth atmosphere and with the interaction between atmosphere and short wave solar and long-wave Earth radiation (fig. 1.1).

When the thickness, the density and the chemical composition of the atmosphere are constant, its mean temperature stabilizes at some level. This level depends on the insolation, on the Earth activity, and on the chemical composition of the atmosphere. Assume that the Earth–atmosphere system is closed and is in a thermodynamic equilibrium state. According to a law of energy conservation, the solar insolation Ψ_{CS} must be equal to the sum of the absorbed Ψ_A and reflected Ψ_o radiation (fig. 1.2):

$$\Psi_{CS} = \Psi_O + \Psi_A \,. \tag{1.1}$$

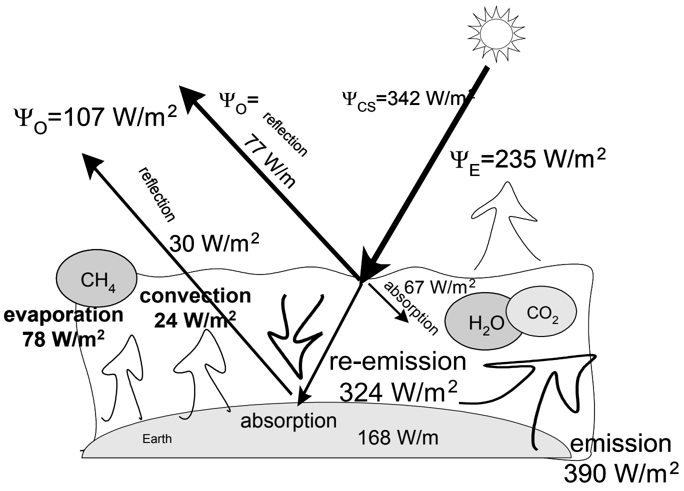


Fig. 1.1. The greenhouse effect

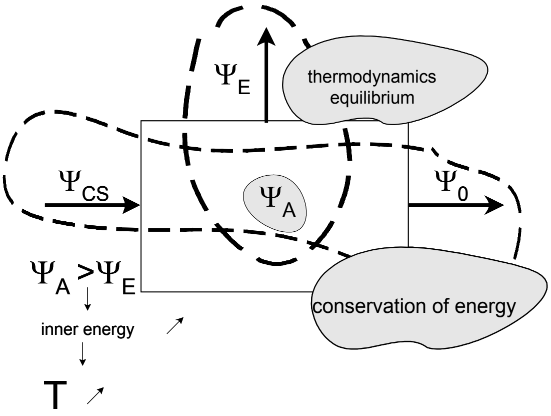


Fig. 1.2. The solar energy conversion in the Earth-atmosphere system

For the system in thermodynamic equilibrium state, the absorbed radiation Ψ_A is equal to the emitted one Ψ_E:

$$\Psi_A = \Psi_E \,. \tag{1.2}$$

When the chemical composition of the atmosphere changes (mainly the concentration of CO_2, CH_4 and H_2O particles), we can notice the disturbance of the greenhouse effect. It is mainly associated with the absorption of the long wave radiation by these particles and, in consequence, the decreasing of the reemitted flux. The result of this effect is the increasing of the atmosphere inner energy and establishing the new equilibrium temperature that is higher than the previous one. Calculating the disturbance of the greenhouse effect associated with the increasing concentration of the greenhouse gases is quite straightforward (equations (1.1), (1.2)).

Of course, it is not the only one factor causing the disturbance of this effect. Other factors are the cyclic changes of the Earth's orbit, solar activity, volcanic activity or a drift of continents. There is no doubt that the all these factors together with the human activity contribute to the observed climatic changes. In figure 1.3 the approximate changes of the mean atmospheric temperature were shown.

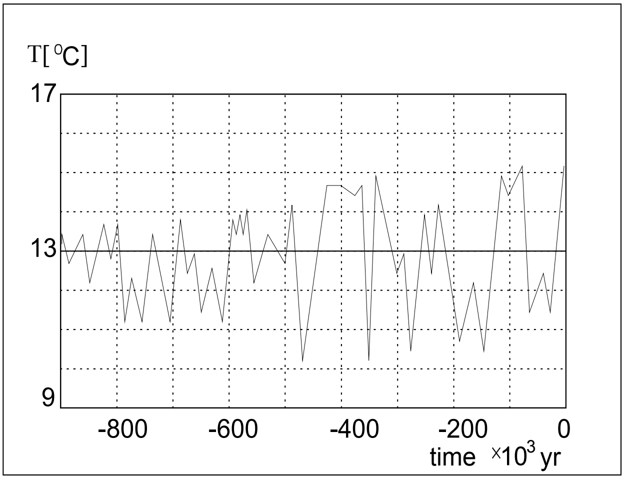


Fig. 1.3. Mean atmospheric temperature changes [1]

We cannot prevent the climatic changes, but we can adapt to the new environment and maybe we can soft the inevitable climatic changes. The main problem to solve is the reduction of the emission of the greenhouse gas such CO_2. We have to be aware that the disturbance of the greenhouse effect is not only one negative effect associated with the atmospheric pollution. The systematic changes of the atmosphere composition generate the flora and fauna world changes, and control the health and condition of our population. Therefore, it is necessary to conduct a systematic activity associated with the limiting the old energy power technology with the simultaneous introducing the new technology based on renewable energy resources [1].

1.2. Some problems of the conventional power industry

The main problem of the conventional energy power system is associated with the limited amount of the beds of natural resources such as coal, gas and petroleum and even radioactive isotopes, needed for nuclear energy power system. And we have to be aware that, after some time, natural resources will be run out. Before it happens, the increasing cost of energy will be observed – proportional to the degree of natural resources depletion and to the energy usage. This time depends on the energy policy. This policy is important for both the exporters and importers of natural resources.

Another very important problem associated with the conventional energy power system, especially with the atmosphere pollution and the depletion of natural resources, is the increasing tendency in average use of energy per capita and the increasing of number of human population (fig. 1.4) [2].

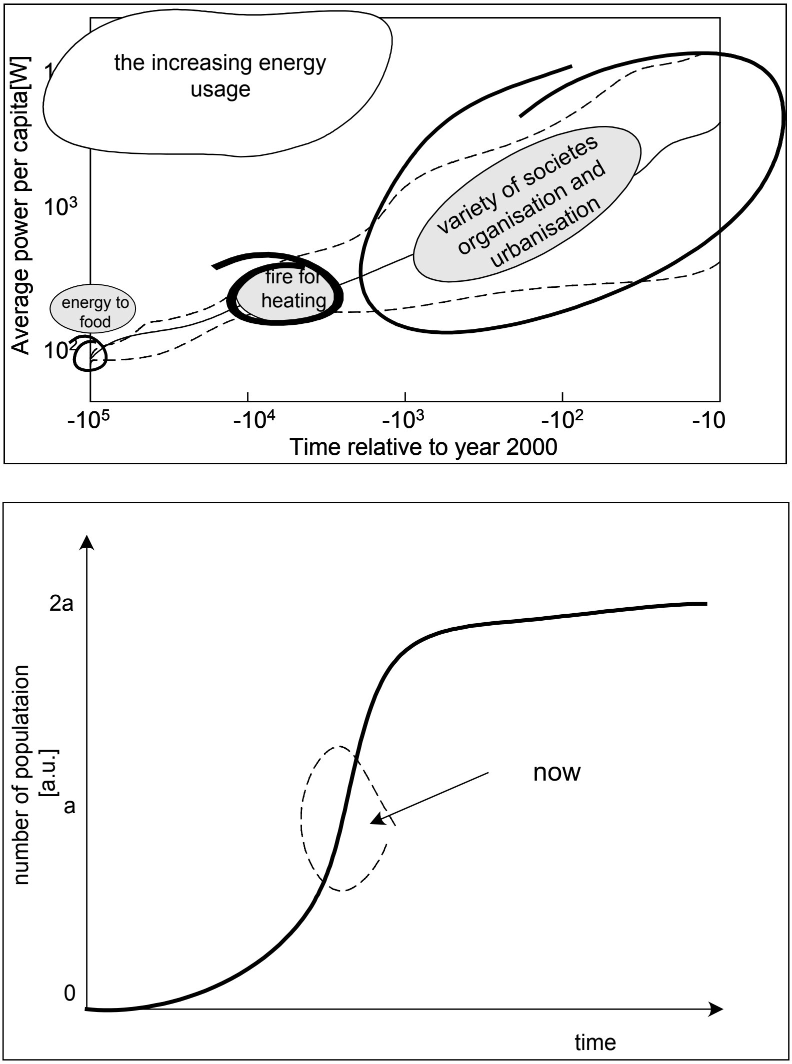


Fig. 1.4. The trend in average use of energy per capita and the tendency of population growth

Now we need a lot of energy for industry, transport, lightening cities and many types of equipment that makes our life easier. We need energy because we have to increase our standard of living, because the number of our population increases, and our lifetime is longer (fig. 1.5).

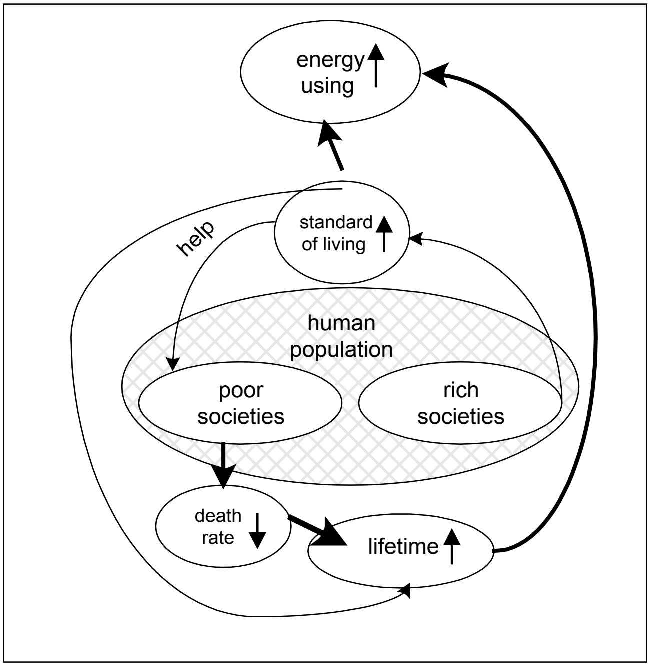


Fig. 1.5. Factors that have a significant influence on the energy use per capita [1]

Now the number of people is about 7 billion with the increasing tempo in 2006 equal to 1.14% [3]. Therefore, it is necessary to develop materials science projects associated with the increasing the efficiency of conventional energy power systems and renewable energy systems (especially photovoltaic thermoelectric materials). This study is very important in renewable energy power systems, because in these systems high investments costs were observed. It is important to lower these costs to an acceptable investment level.

1.3. The renewable energy sources

Due to the limited amount of natural resources (for conventional energy power system power), we have to intense the utilization of renewable energy sources. But this activity is closely associated with the progress of new materials technologies.

In figure 1.6 shows different sources of renewable energy such as: solar radiation, wind, tides, ocean waves, water flows, geothermal flows, heat stored in the Earth and biological conversion.

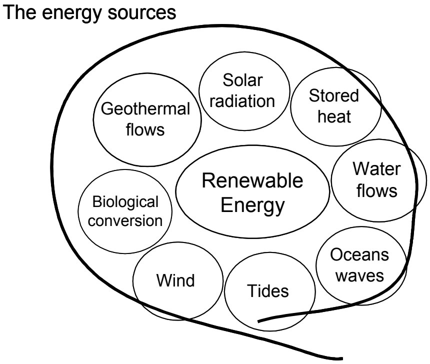


Fig. 1.6. The renewable energy sources

Most of these sources are caused by solar radiation. The phenomena that can be used in renewable energy power system are shown in fig. 1.7.

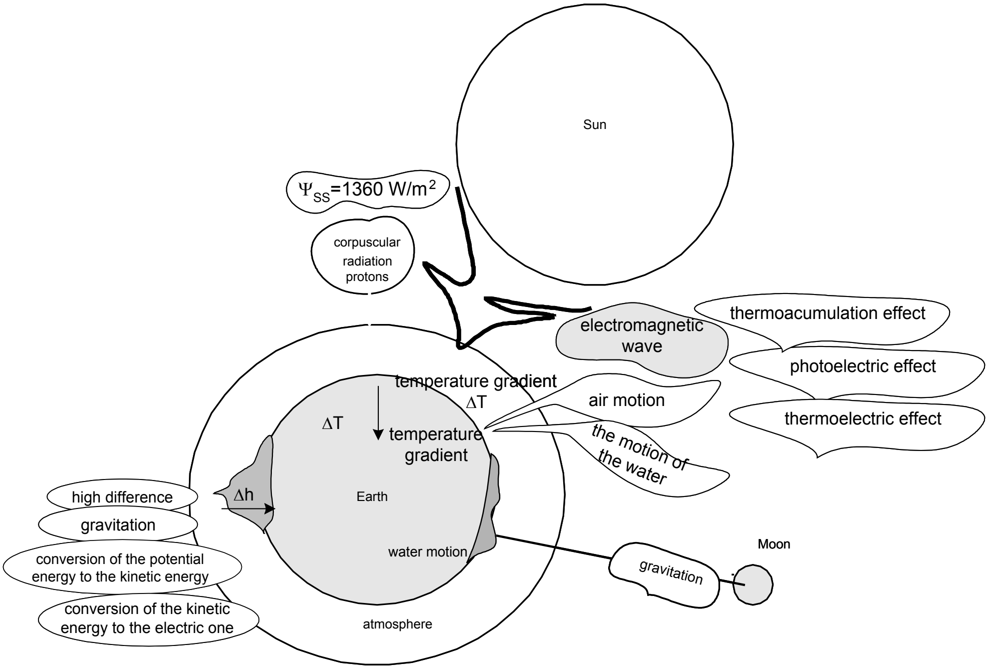


Fig. 1.7. The renewable energy sources in the Earth–Sun–atmosphere system

Solar radiation interacts with the Earth–atmosphere system. As a result of this interaction some interesting phenomena were observed, such as:

- Wind – associated with the solar radiation absorption by the Earth atmosphere that creates the temperature gradient, and, as a consequence, the air motion,
- Streams and waves – associated with the solar radiation absorption by the water (ocean) that creates the temperature gradient, and, as a consequence, the water motion
- Water flows – associated with the solar radiation absorption by the plants and water, and, as a consequence, the evaporation phenomena and water circulation (feeding a river with water)
- Photosynthesis that leads to biomass production.

The Sun is the most important source of renewable energy. Solar energy that comes to the top of the Earth's atmosphere is equal to about 1360 W/m^2. It means that an average square meter of the Earth's surface gets about 1360 J of energy every second. It gives, during the year, the power assessed at about $12*10^{16}$ W [4]. At the Earth's surface this energy is a little lower because of the absorption and reflection phenomenon.

The gravitational interaction is another, very important, source of renewable energy. In our system there are two bodies that are the sources of the gravitation force – the Moon and Earth. When the Moon interacts with the water in oceans the tides are observed, and when the Earth interacts with the water in rivers the flow of water and the waterfalls were observed. The gravitational Moon-water and Earth/water interaction has a potential of about $3*10^{12}$ W [5]. It means that every year we can develop $3*10^{12}$ J.

The geothermal energy associated with the chemical and radioactive inside the Earth is the source of heat energy that can be used in the power system (potential $3*10^{13}$ W) [5].

The potential of the renewable energy stored in the Sun-Earth-atmosphere system is very high. The most interesting is solar energy, because the Sun is the largest source of renewable energy. The insolation in some places depends on the latitude, solar azimuth and altitude, cloudiness and time. But even in Poland, where the weather conditions are not very good, the observed insolation seems to be enough for heating (by collectors) the house (meaning a few kWh by square meter during the day). The Sun is a very important renewable source of energy, because every day it emits the radiation irrespectively of the political and economical situation. The only problem is the price of the equipment that converts the solar radiation energy to heat or electricity.

The most convenient form of energy is the electric one. Electricity can be obtained in a conventional conversion system based on coal, gas, petroleum or biomass burning, or in a modern system based on the direct conversion based on the photo effect and thermo-effect. Figure 1.8 it shows the scheme of renewable energy conversion processes when the result is electricity.

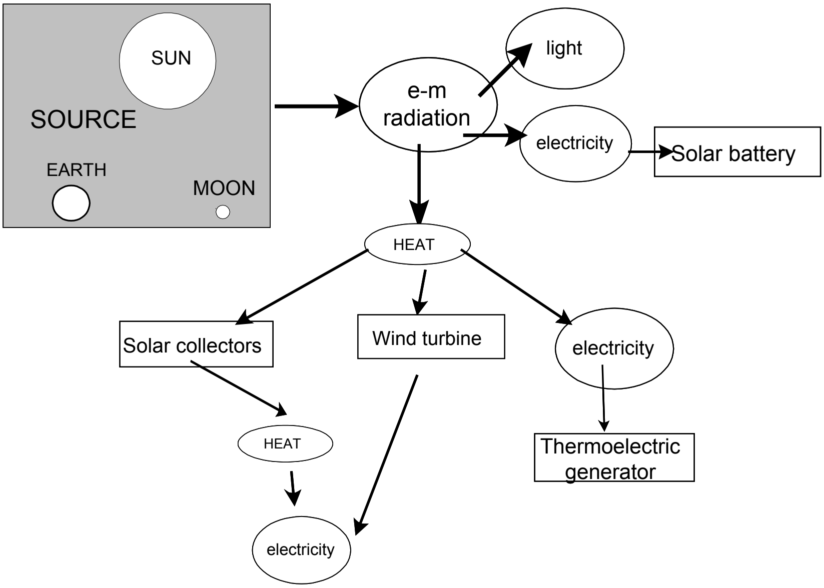


Fig. 1.8. The scheme of renewable energy conversion processes

1.4. The conversion of the heat stored inside the Earth

The heat stored inside the Earth is a consequence of some radioactive reactions and the absorption of electromagnetic waves phenomena. As a result of these processes the temperature at some depth is constant during a year and equal to the mean value for the air temperature (for example in Poland at the 10 m depth the ground temperature is equal to 7–8 °C. The idea of utilizing this energy is based on such processes as:

- Transfer of the heat energy from the ground to the heat transfer medium,
- Evaporation phenomena of the heat transfer medium with a low value of evaporation temperature,
- Compression process and thermodynamic phenomena associated with the Clapeyron's equation:

$$\frac{p \cdot V}{T} = \text{const}, \tag{1.3}$$

- The condensation process and the energy conversion associated with the condensation process.

The idea of utilizing the heat stored inside the Earth, by the heat pump, is shown in fig. 1.9. For this process it is needed to deliver the energy from the outside (electricity) to compress the working agent. But the energy profits are sufficient for primary heating and air conditioning. The efficiency of the heat pump (COP-coefficient of performance) is defined as the ratio of the generated heat and the energy used to do it. COP depends on the temperature of the heat source. It is higher for higher temperature of the upper source, and allows to determine how much heat can be acquired using a unit of electrical energy.

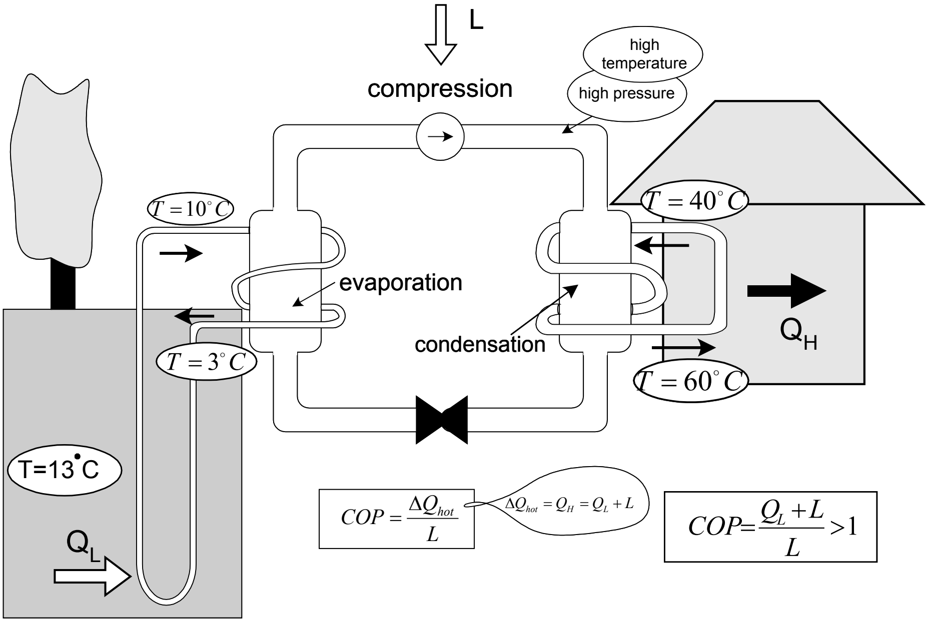


Fig. 1.9. Utilizing the energy stored inside the Earth

In the presented heat pump, the medium with low evaporation temperature, circulates in the piping system between the evaporator (outside the house) and compensator (inside the house), and is a carrier of energy from the outside to the inside – when it was cold (winter) and from the inside to the outside – when it is hot (summer) – the reversal option.

1.5. Electricity production

In photovoltaic and thermoelectric equipment, and in a system with a fuel cell, simplifying of the energy conversion process to the form of electric one was observed.

It means that the electromagnetic radiation (in PV elements), heat or IR radiation (in thermoelectric. generators) and chemical energy stored in the chemical compounds (fuel cell) are converted directly to electricity. But this type of conversion demands the progress in materials science. It is necessary to develop a research of materials with specific properties such as ionic conductors (for fuel cells), thin film or polymer semiconductors (for solar batteries), thermoelectric materials (for thermoelectric generators). The progress in materials science, and the popularization of renewable energy systems power based on the PV and thermoelectric generators and fuel cells, will have a lot of profits for people and for our environment in future. The best profit is simplifying the electricity "production" process by a direct conversion solar energy to electric one. The second and important profit is the limitation of the energy system power monopoly. Another profit is the reduction of air, water and ground pollution that allows us to protect the nature for the next generations and to smooth the depletion of natural resources (fig. 1.10).

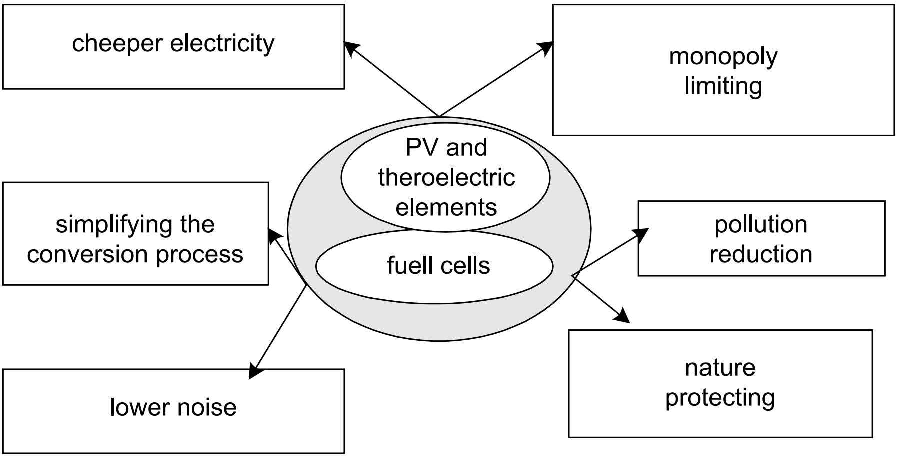


Fig. 1.10. The profits of developing the renewable energy systems based on PV and thermoelectric elements and fuel cells [1]

The photovoltaic direct conversion of the solar radiation to electricity is based on the photo effect in semiconductors. The main idea of this phenomenon is shown in fig. 1.11. The PV devices are based on the semi-conducting materials. For example, in the type *p* semiconductor, the weakly bounded electron associated with the fifth valence ion absorbs solar radiation. After this process the electron has a higher energy and comes to the conduction band. When this energy is enough to break off the chemical binding, the electron can move away (creating the electron-hole pair). Next this free electron can move towards the electrode or can relax (coming back to the donor). During solar irradiation it was created the electron-holes pairs and it is highly probable that this pair will disappear in the relaxing process. To prevent this the *p–n* junction was formed. Figure 1.12 shows the mechanism of the electrons and holes migration across the *p–n* junction [6].

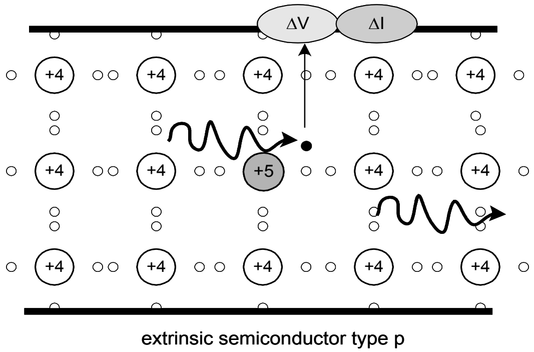
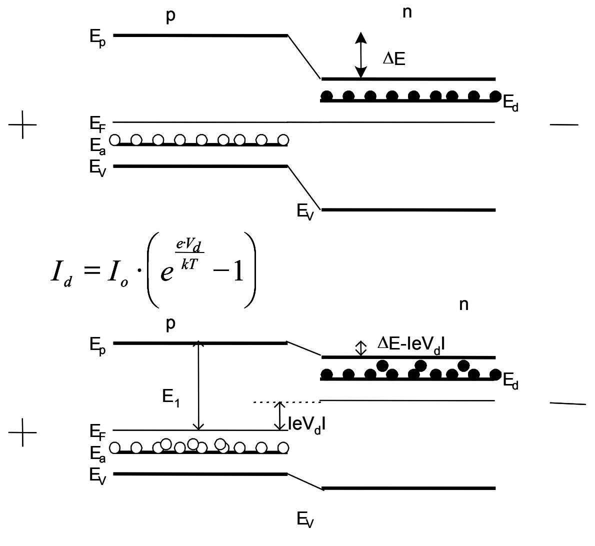


Fig. 1.11. The PV effect in doped semiconductors



$$I_d = I_o \cdot \left(e^{\frac{e \cdot V_d}{kT}} - 1 \right)$$

Fig. 1.12. The *p–n* junction

On the *p* side of the *n–p* junction, we have mobile holes and on the *n*-side-mobile electrons. The holes drift by diffusion across the junction towards the *n*-part and leave at the *p*-part immobile negative charge. The electrons drift in the opposite direction and leave at the *n*-part the immobile positive charge. These immobile charged atoms create an electric field. This field works against the movement of holes and electrons across the *n–p* junction and opposes and quickly stops holes and electrons diffusion. When the light appears, the weakly bounded electrons absorb the electromagnetic radiation, leave the atoms and generate the electron-hole pairs. If this photon generation of electric carriers occurs near the *n–p* junction, the energy level at the *n*-side of the junction rises. As a result of this process the Fermi level at the *n*-side of the *n–p* junction is $e \cdot V_d$ higher than at the *p*-side.

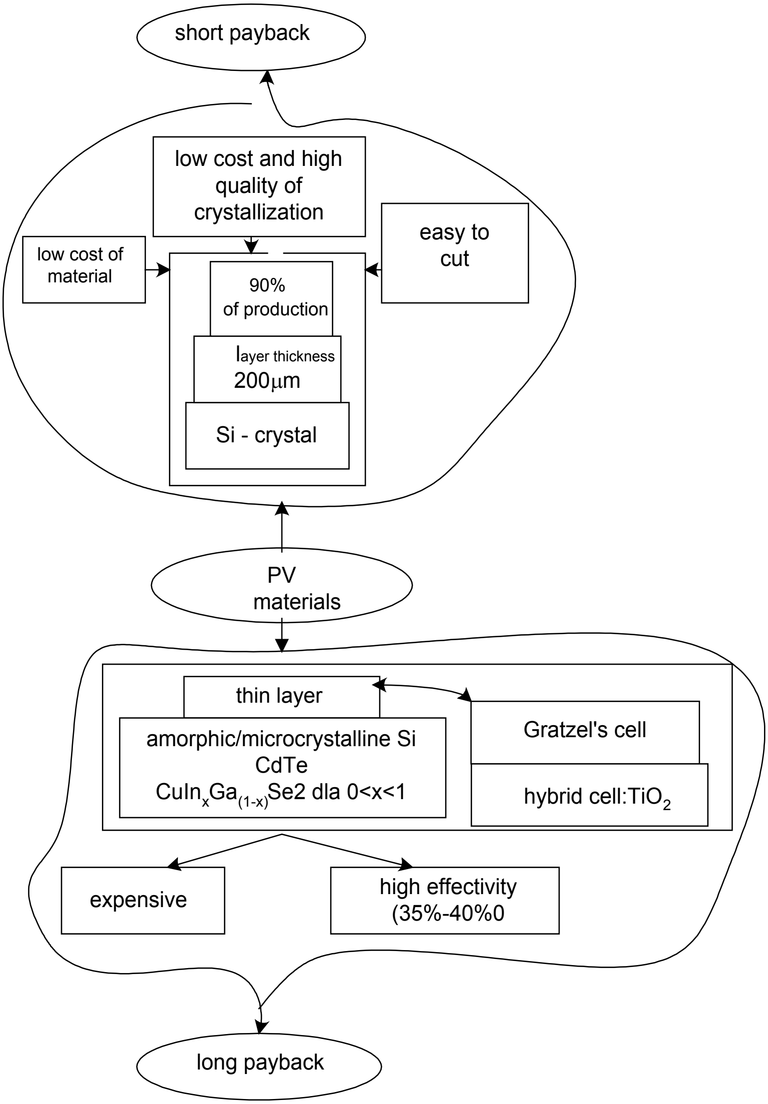


Fig. 1.13. PV devices – economic possibility

Thus the photo-current is observed:

$$I_d = I_0\left(e^{\frac{e\cdot V_d}{kT}} - 1\right). \tag{1.4}$$

The PV devices will have a future in built-up areas due to the wide availability and opportunity to use PV elements as construction elements such as tiles or elevation. The creation of small local micro electric system powers causes the reduction of electric power grids. But it is need to develop materials science to obtain cheaper and most effective PV elements. Now the cheap PV elements are only a few percent effective. The most effective thin layer junctions have a 40% effectively but they are too expensive. The reducing of PV cost can be obtained by creating the tax law (government intervention) or by developing materials science. The increasing of the production associated with the introducing new materials and new technologies, led to the lowering of the energy production costs in Europe from 1 €/kWh in 1999 year to 0.2–0.44 €/kWh in 2007 [5].

Figure 1.13 shows the main information about the different PV cells. There are two main PV cells:

- Silicon PV cells based on crystalline silicon,
- Thin layer PV.

The silicon PV cells are not very expensive but their effectivity is relatively low – about a few percent. The higher effectivity characterizes the thin layer PV cells. For example, the triple junction GaInP/GaAs/Ge is 40% effective. The high costs of PV elements result in the long payback. The long payback repels the investors to use devices based on such PV elements.

The payback depends not only on the capital costs. The factor associated with the utilizing the solar energy is insolation.

1.6. Insolation

Insolation depends on the geographic location, climate, season of the year and time of the day. The source of insolation is the Sun (about $1.4 \cdot 10^6$ km diameter) that emits electromagnetic and corpuscular radiation as a result of hydrogen to the helium fusion reaction. These reactions give power equal to about $3.8 \cdot 10^{20}$ MW.

The insolation (Ψ), defined as a solar flux striking the surface, depends on the mutual Earth and Sun position (fig. 1.14).

As it is shown in fig. 1.14, insolation is closely associated with:

- the location of the observer represented by the value of the observer's latitude L,
- time of day represented by the hour angle H and equal to the time that has passed since the noon (in hour) multiplied by 15 angle degree,
- a season represented by the angle of solar noon β_N.

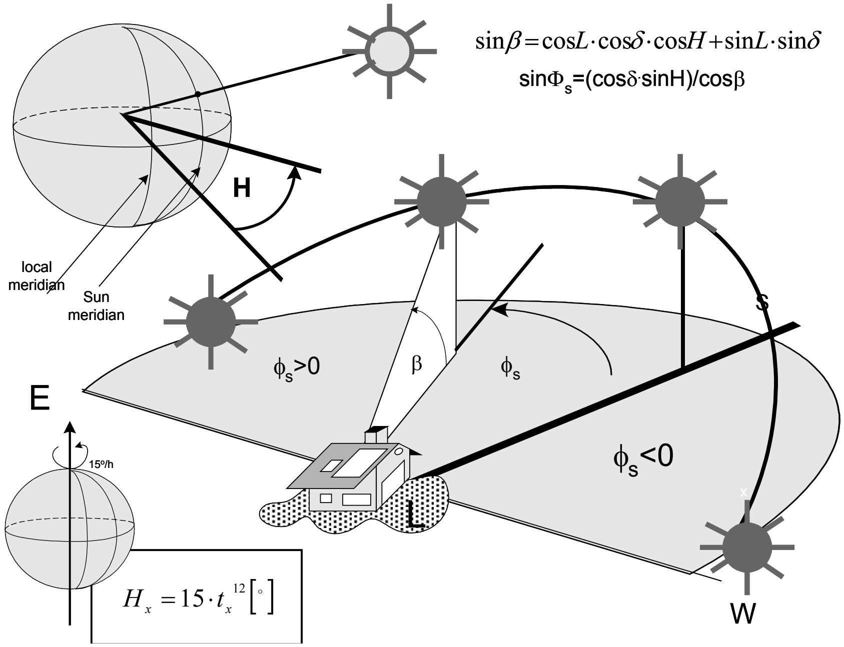


Fig. 1.14. The Sun altitude and azimuth

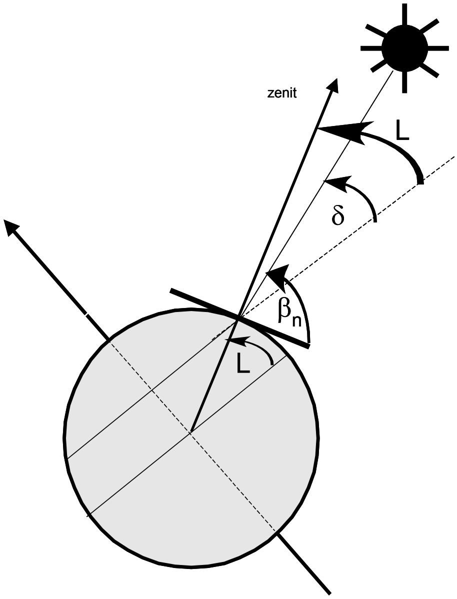


Fig. 1.15. The relations between the latitude *L*, declination *δ* and the solar altitude at the noon β_n

The solar altitude and azimuth is a consequence of the Earth movement around the Sun at the elliptic orbit and the inclination of the Earth axis to the orbit's surface. Figure 1.15 shows the relations between the latitude L, solar declination δ and solar altitude at the noon β_n. When the latitude and solar declination changes during the rotational Earth movement around its axis and around the Sun, the solar altitude β and azimuth Φ changes too.

The relations between: the latitude, hour angle, day number, altitude and azimuth are as follows [6]:

$$\delta = 23.45 \sin\left(\frac{360(n-81)}{365}\right) \tag{1.5}$$

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \tag{1.6}$$

$$\sin\Phi = \frac{\cos\delta \sin H}{\cos\beta} \tag{1.7}$$

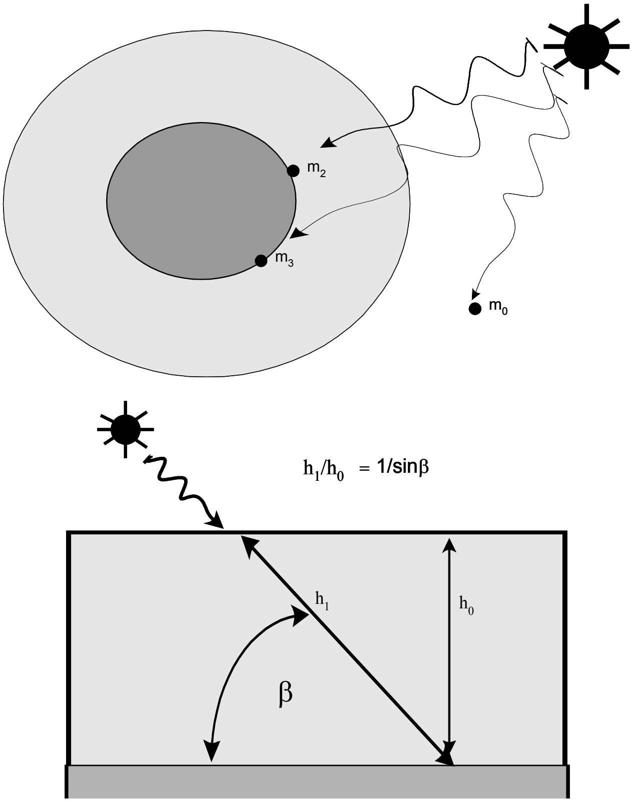


Fig. 1.16. The air mass ratio *m*

Insolation depends on the thickness of the atmosphere (optical depth). The optical depth is described by the air mass ratio m defined as (fig. 1.16):

$$m = \frac{1}{\sin \beta}. \tag{1.8}$$

Insolation depends on the latitude L, solar declination δ and the hour angle H. It is possible to estimate insolation at any place on the Earth and at any time. To do this, assume that our observer is located at the latitude L degrees north and that he/she wants to estimate insolation at some surface S (fig. 1.17). Of course, our observer has to bear in mind that his/her surface is penetrated not only by the direct solar beam (Ψ_0).

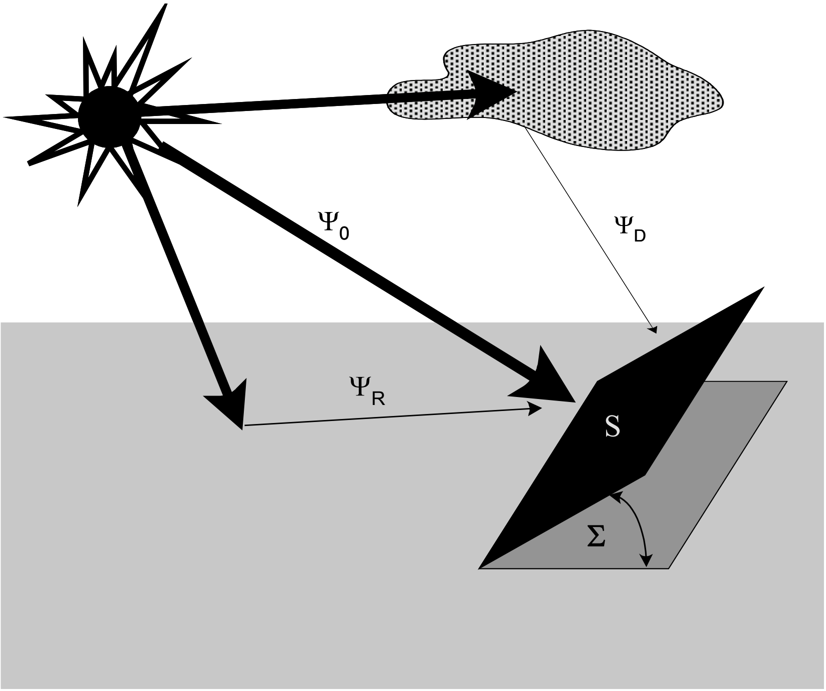


Fig. 1.17. The insolation of the collector

When it is a cloudy day the surface is penetrated by diffuse radiation (Ψ_D). When in the vicinity of the collector are the surfaces that reflect the solar radiation, one has to take into account the reflected beam (Ψ_R). On a sunny day the direct beam is the most important part of insolation, but the diffused one and reflected one have some contribution that can't be neglected. As it was shown in figure 1.18, the very essential factor that influences the total insolation of the surface S is the collector tilt angle Σ.

The insolation of the surface depends on its tilt angle Σ, on the solar altitude β solar azimuth Φ_s and collector azimuth Φ_c (fig. 1.18).

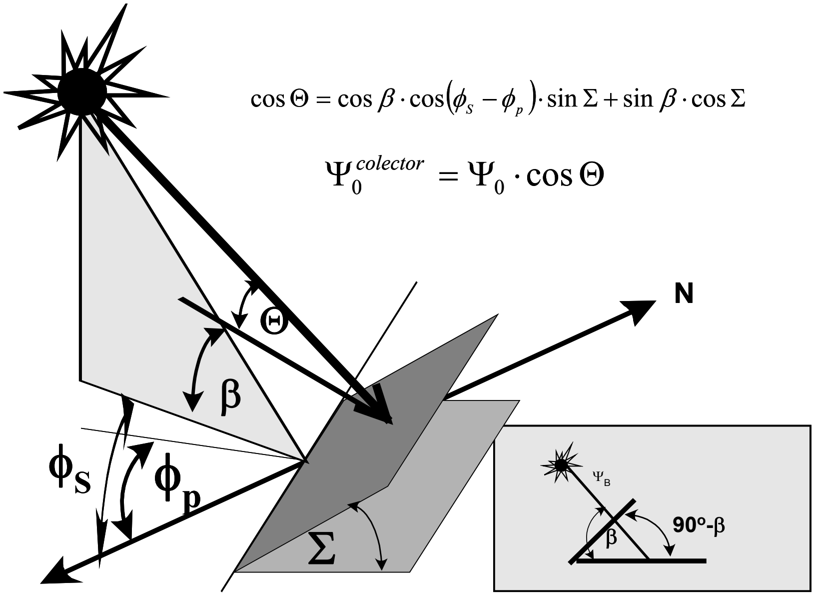


Fig. 1.18. The incidence angle between the sun and collector face Θ in relation with the Sun position (Φ_S, β) and collector position (Σ, Φ_p)

According to a clear sky model, the direct, diffused and reflected beams depend on the day number in a year (n), on the extraterrestrial solar insolation (Ψ_S^S) and on the collector orientation (Φ_c), and can be mathematically described by the following relations [6]:

$$\Psi_S^S = 1377 \cdot \left[1 + 0.034 \cdot \cos\left(\frac{360 \cdot n}{365}\right)\right], \tag{1.9}$$

$$\Psi_0^{\text{colector}} = a(n) \cdot \left(\cos\beta \cos\Delta\Phi \cdot \sin\Sigma + \sin\beta \cdot \cos\Sigma\right) \cdot \exp\left[-\frac{b(n)}{\sin\beta}\right], \tag{1.10}$$

$$\Psi_D^{\text{colector}} = c(n) \cdot a(n) \cdot \left(\frac{1 + \cos\Sigma}{2}\right) \exp\left[-\frac{b(n)}{\sin\beta}\right], \tag{1.11}$$

$$\Psi_R^{\text{colector}} = \rho \cdot a(n) \cdot \left(\frac{1 - \cos\Sigma}{2}\right) \cdot (\sin\beta + c) \exp\left[-\frac{b(n)}{\sin\beta}\right], \tag{1.12}$$

where

$$a(n) = 1160 + 75 \cdot \sin\left[\frac{360}{365}(n - 275)\right], \tag{1.13}$$

$$b(n) = 0.174 + 0.035 \cdot \sin\left[\frac{360}{365}(n - 100)\right], \tag{1.14}$$

$$c(n) = 0.095 + 0.04 \cdot \sin\left[\frac{360}{365}(n - 100)\right], \tag{1.15}$$

$$\mathit{\Delta\Phi} = \mathit{\Phi}_s - \mathit{\Phi}_c \,. \tag{1.16}$$

On the basis on the relations 2–8, insolation at any place and at any time can be estimated with quite good precision. For example, in Kraków (L = 50°), on 6th December (n = 341), for the collector tilted at 52° ($\mathit{\Sigma}$= 52°) and with the azimuth equal to 20° ($\mathit{\Phi}_C$ = 20°) at noon, the following values of insolation were obtained:

$$\mathit{\Psi}_0^{\text{collector}} = 663.9\ \frac{\text{W}}{\text{m}^2}, \tag{1.17}$$

$$\mathit{\Psi}_D^{\text{collector}} = 35.3\ \frac{\text{W}}{\text{m}^2}, \tag{1.18}$$

$$\mathit{\Psi}_R^{\text{collector}} = 10.2\ \frac{\text{W}}{\text{m}^2}. \tag{1.19}$$

These values are estimated assuming the clear-sky model. On a cloudy day one has to take into account the clearness index (k_T), which is the ratio of the average horizontal insolation at the site $\overline{\mathit{\Psi}}_H$ to the extraterrestrial insolation on a horizontal surface above the site and outside the atmosphere $\overline{\mathit{\Psi}}_o^a$:

$$k_T = \frac{\overline{\mathit{\Psi}}_H}{\overline{\mathit{\Psi}}_o^a}, \tag{1.20}$$

where

$$\mathit{\Psi}_0^a = \left(\frac{24}{\pi}\right) \cdot SC \cdot \left(\cos L \cos\delta \cdot \sin H_{SR} + H_{SR} \sin L \cdot \sin\delta\right) \cdot \left[1 + 0.034 \cos\left(\frac{360 \cdot n}{365}\right)\right]. \tag{1.21}$$

The fraction of the horizontal diffused insolation ($\overline{\Psi}_{DH}$) is correlated with the average horizontal insolation ($\overline{\Psi}_{H}$) by the Liu–Jordan relation [6]:

$$\frac{\overline{\Psi}_{DH}}{\overline{\Psi}_{H}} = f(k_T) = 1.390 - 4.027 \cdot k_T + 5.531 \cdot k_T^2 - 3.108 \cdot k_T^3 . \tag{1.22}$$

The total insolation on the collector surface ($\overline{\Psi}_{\text{total}}^{\text{collector}}$) is a sum of diffused, reflected and direct components:

$$\overline{\Psi}_{\text{total}}^{\text{collector}} = \overline{\Psi}_{H} \left[\left(1 - f(k_T)\right) \cdot R + f(k_T) \cdot \frac{1 + \cos \Sigma}{2} + \rho \cdot \frac{1 - \cos \Sigma}{2} \right] . \tag{1.23}$$

Where ρ is the reflectance of the surface in front of the collector and R is the average beam tilt factor that is dependent on the site latitude L, the tilt of the collector Σ, declination δ sunrise hour angle H_{SR}:

$$H_{SR} = \arccos\left(- \operatorname{tg} L \cdot \operatorname{tg} \delta\right) \tag{1.24}$$

and sunrise hour angle for the collector H_{SRC}

$$H_{SRC} = \min\left\{\arccos\left(- \operatorname{tg} L \cdot \operatorname{tg} \delta\right), \arccos\left(- \operatorname{tg}(L - \delta) \cdot \operatorname{tg} \delta\right)\right\} . \tag{1.25}$$

When we consider the real conditions for Kraków in December, obtained on 6th December, the energy from the Sun (for each square meter of collector) is equal to about 4.6 kWh.

Some solar energy profits can be obtained utilizing the single-axis and two-axis systems tracking. The idea of these systems is shown in fig. 1.19.

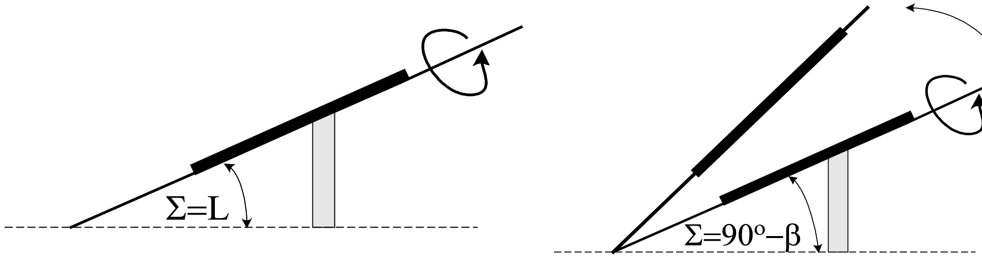


Fig. 1.19. The single-axis and two-axis tracking systems

In figure 1.20 there is calculated insolation on the collector surfaces located horizontally, tilted at optimal angle and in single-axis and two-axis systems.

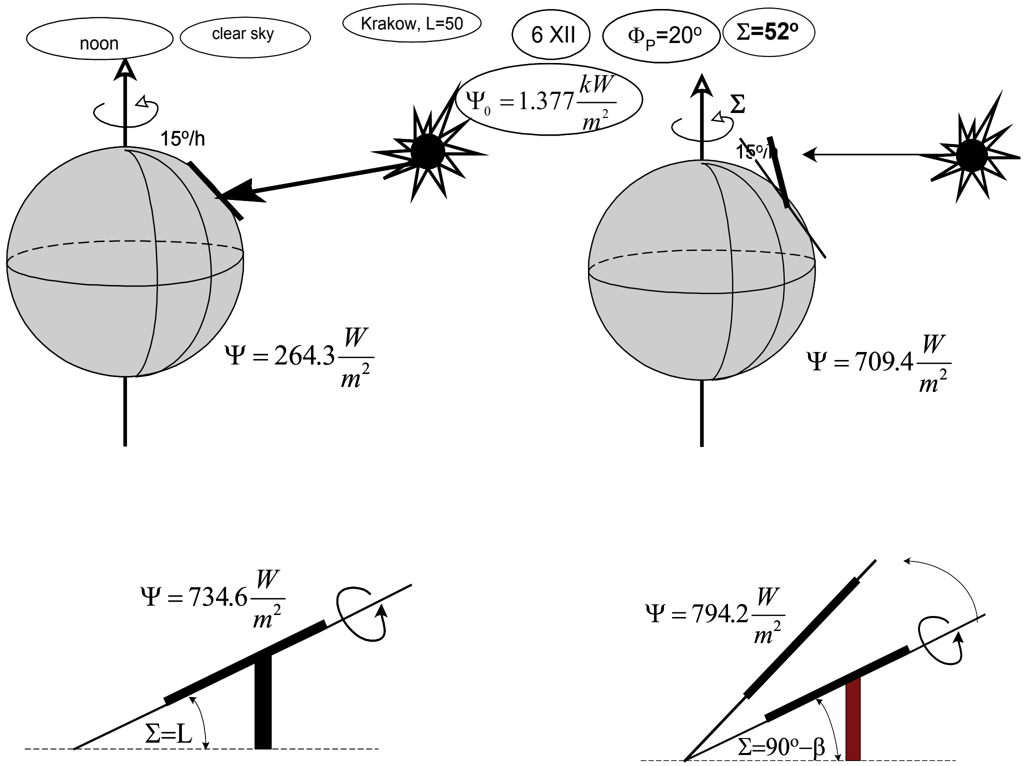


Fig. 1.20. The insolation of the horizontal and tilted collector and one-axis tracking and two-axis tracking systems

1.7. Thermoelectric generation

The solar radiation can be converted to the electric one by using photoeffect (PV elements) or thermoeffects. The thermoeffect is associated with the interaction of the Sun radiation with the gas of electrons in thermoelectric materials. As a result of this interaction, according to the Clapeyron’s relation, the gradient of concentration of the electricity carriers and finally, the voltage was observed. When it was assumed that the electron gas is an ideal gas, the Clapeyron’s relation can be used to describe the processes in metal:

$$P\cdot V = n\cdot R\cdot T\ , \tag{1.26}$$

where P is a pressure, V is a volume, T is a temperature in K, R is a gas constant and n is the concentration of electrons.

Because the material, as a whole, is a solid state, we can assume that:

$$P = \text{const}, \tag{1.27}$$

$$V = \text{const} . \tag{1.28}$$

It means that:

$$n \cdot T = \text{const}. \tag{1.29}$$

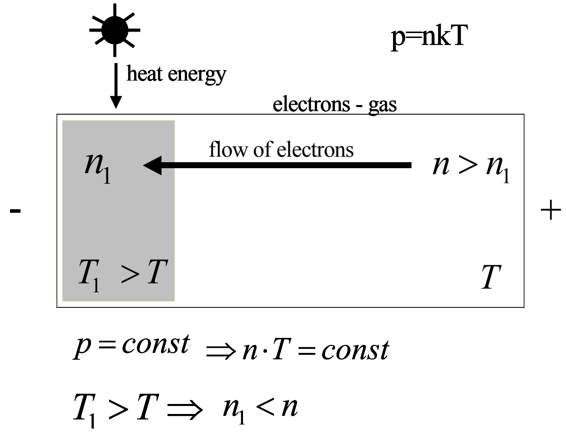


Fig. 1.21. The Seebeck effect in metals

When the electromagnetic solar radiation is absorbed by the material, the temperature of one side of element becomes higher than the another one. But the concentration of the electrons depends on the temperature. As a result, the concentration of electrons is higher at the hotter side of the element. It means that the gradient of temperature involves the gradient of concentration. But the gradient of concentration causes the diffusion of these carriers. As a result of the diffusion process, voltage is observed (fig. 1.21). It is the Seebeck effect

In semiconductors we have no gas of electrons, but the concentration of electric carriers depends on the temperature according to the following relation:

$$n_{e,h} = n_0 \cdot e^{-\frac{E}{k \cdot T}}, \tag{1.30}$$

where k is the Boltzmann constant, T is temperature in the Kelvin scale and E is the energy the electrons activation (e) or holes (h) motion.

The generation of electricity by using the thermoelectric phenomena is very important in spacecrafts, that are in a long distance from the Sun. Near the Sun, a solar panel can be used for electricity production. But when the solar insolation is too small, the radioisotope thermoelectric generators convert the nuclear energy to electricity.

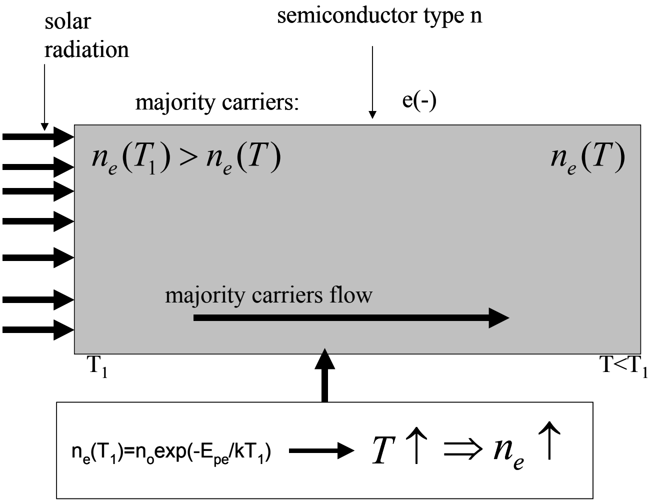


Fig. 1.22. The Seebeck effect in semiconductors

1.8. The black body

The phenomenon that plays a very important role in utilizing the solar radiation, as a source of energy for heat energy generation, is the thermoaccumulation effect.

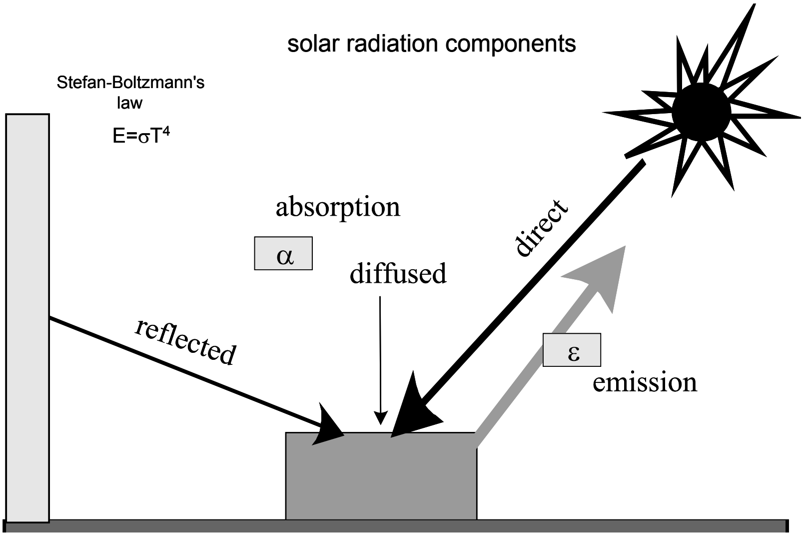


Fig. 1.23. The solar radiation components

Imagine the collecting surface made of the some material with absorption coefficient equal to α, and emission coefficient equals to ε. When this surface is exposed to the solar radiation (direct, diffused and reflected one), it interacts with the electromagnetic radiation. As a result of the absorption and emission processes (fig. 1.23), the thermodynamic equilibrium is achieved.

In the thermodynamic equilibrium state the temperature of the collecting surface remains constant. The value of the temperature depends on the value of the absorption and emission coefficients.

The solar radiation penetrates the material and some its part is absorbed. During this process the interaction between the electromagnetic solar radiation and the collector's molecules and atoms is observed (fig. 1.24). The photons interact with the valence electrons and, as a result of this process, the electrons are excited. When the photon energy is high enough, the electric carriers are created, when it is smaller – the valence electrons are excited and the phonon energy is increased.

The inner energy and of course the temperature of the collecting surface increase. The intensity of the radiation, during the penetration of the collecting surface, is reduced according to the Lambert–Beer law:

$$J = J_0 \cdot \exp(-\mu \cdot x)\,, \tag{1.31}$$

where x is the depth of material and the coefficient μ has three components: diffused, associated with the creation of electric carriers and thermal – associated with the inner energy of the material.

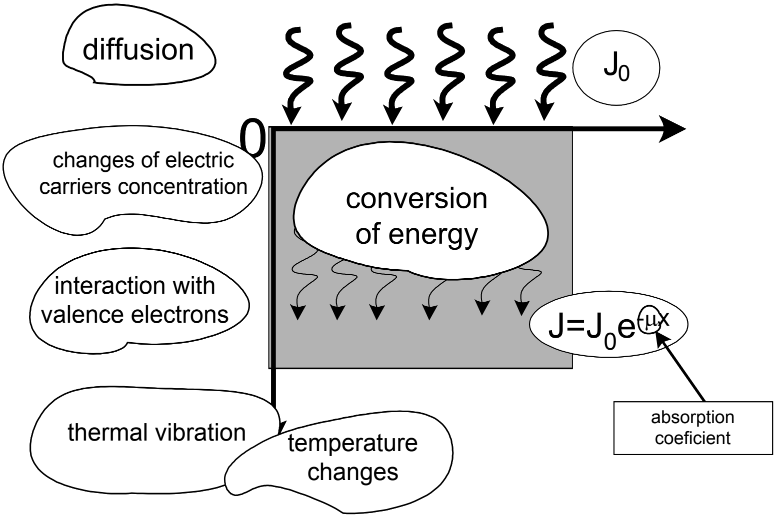


Fig. 1.24. The processes of energy conversion associated with the absorption of solar radiation

Now we neglect the processes associated with the diffusion and carriers creation and assume that collecting surface is a black body. The model of the black body is presented in fig. 1.25.

The black body has the absorption coefficient α that is independent of the frequency of the absorbed radiation and is equal to one. If the collecting surface, which is treated as the black body, is in the thermodynamic equilibrium the emitted power flux density is equal to the absorbed one.

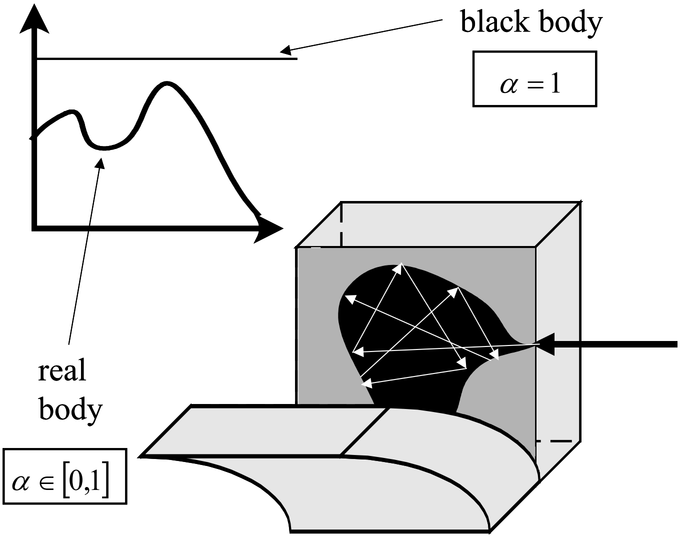


Fig. 1.25. The black body model

For the black body the emitted power flux density is proportional to the temperature to the fourth, according to the Stefan–Boltzmann law:

$$\Psi_{\text{emited}} = \sigma \cdot T^4 , \tag{1.32}$$

where σ is the Stefan–Boltzmann constant and T is the temperature in K.

In the thermodynamic equilibrium:

$$\Psi_{\text{emitted}} = \Psi_{\text{absorbed}} . \tag{1.33}$$

For the real body the absorption coefficient is smaller than one. Assume that collecting surface has some absorption properties represented by the coefficient α and some emission properties represented by the emission coefficient ε. In this case, the equilibrium state is described by the following relation:

$$\varepsilon \cdot \Psi_{\text{emitted}} = \alpha \cdot \Psi_{\text{absorbed}} . \tag{1.34}$$

When the collecting surface is covered by a transparent layer with the emission coefficient $\varepsilon = 1$ and located in the environment at the temperature T_0, then after some time the thermodynamic equilibrium will be observed. The equilibrium temperature T depends on the absorption and emission properties of the transparent layer and collector surface, represented by α and ε coefficients and on the heat conduction represented by the h coefficients (fig. 1.26).

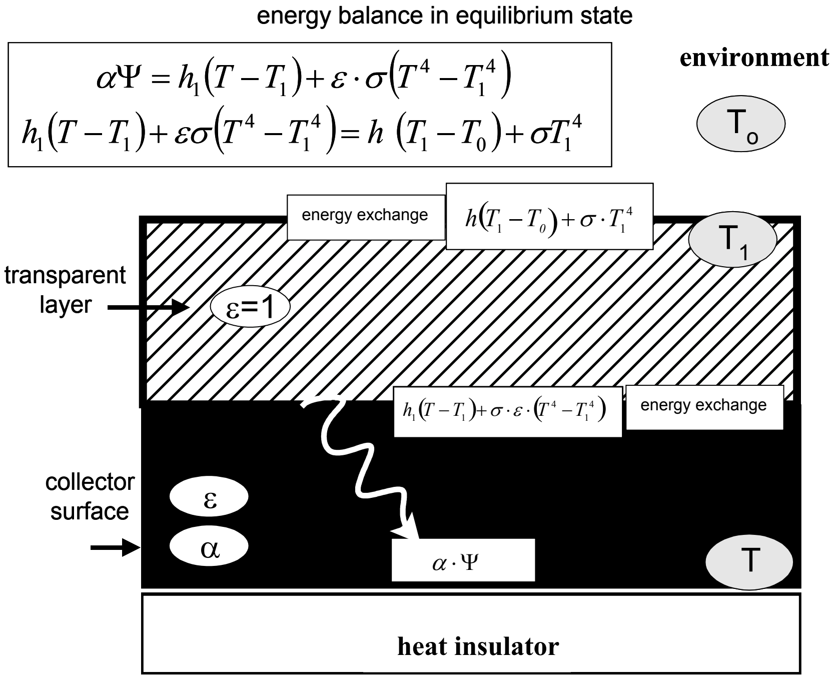


Fig. 1.26. The energy streams in the system: heat insulator–collector–transparent layer

The equilibrium temperature of the collecting surface can be increased by technical solutions (for example applying solar concentrators).

1.9. The alkali metal thermal electric conversion

There are some materials with very interesting properties as renewable energy power system from an engineer's point of view. To this group belong the materials that are excellent conductors of some alkali metals but bad conductors of electrons (called ionic conductors). The equipment based on such materials is called AMTEC (alkali metal thermal electric converter). The main ionic conductor is called BASE (β-alumina solid electrolyte). Figure 1.27 shows the idea of the energy conversion process by using ionic conductor material.

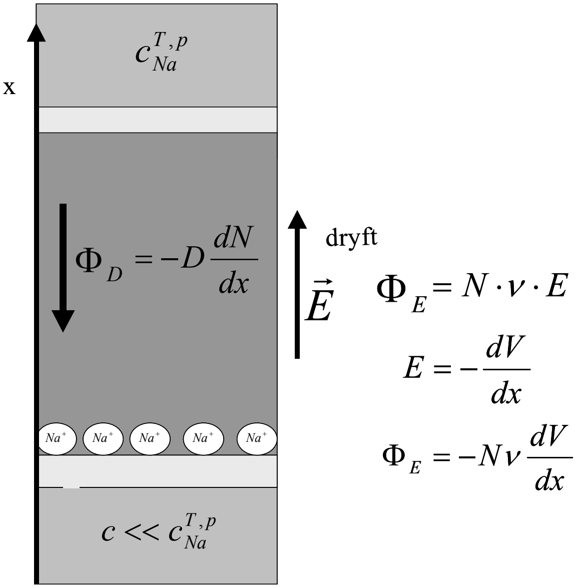


Fig. 1.27. The idea of AMTEC cell

Imagine that at the opposite site of the AMTEC based on the BASE material, is the gradient of sodium ions concentrations. The concentration of Na^+ ions at the top is $c_{\mathrm{Na}}^{T,p}$ and at the bottom is c. The concentration of the sodium ions at the top is much higher that at the bottom:

$$c_{Na}^{T,p} >> c\,. \tag{1.35}$$

Because of the gradient of concentration, the sodium ions migrate through the ionic conductor. This migration cause the creation of the diffusion flux Φ_D that is proportional to the diffusion coefficient D and the gradient of concentration ${dN}/{dx}$ according to the following relation:

$$\Phi_D = -D\frac{dN}{dx}\,. \tag{1.36}$$

This migration causes the diffusion of sodium ions from the top of the BASE slab to its bottom site, and, as a result of this process, the difference of the electric charge concentration. In such a way the electric field E is created. Next to this field appears driving flux Φ_E in the opposite direction to the diffusion:

$$\Phi_E = N \cdot \mu \cdot E\,. \tag{1.37}$$

The energy (W) that can be obtained by μ-kilo moles of sodium gas that expands from pressure p_A to the p_C is equal to:

$$W = \mu R T \ln \frac{p_A}{p_B}\,, \tag{1.38}$$

where R is the gas constant and T is the temperature.

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Chapter 2

Selected problems of photo-thermal renewable resources systems

This chapter describes the various applications of photo-thermal renewable resources systems. Regarding the way of utilization the energy from solar radiation these systems are divided into three main groups: passive photo-thermal systems, active photo-thermal systems and supported systems. Each group has a specific construction and is dedicated to different purposes e.g. warming domestic water, central heating or cooling of houses, upper heat source or supporting of electricity production. The simple construction and low invest costs cause that these solutions are very popular even in a temperate climate where the solar conditions strongly vary during a year.

2.1. Passive photo-thermal systems

Passive photo-thermal systems are the simplest solutions, which base on direct conversion of solar energy into heat. These renewable resources systems are usually use for heating of houses or buildings, warming up water in a domestic warm water net or outside water reservoirs, drying wood or agricultural products [2, 5, 7, 8]. They do not require additional energy necessary to drive engines, compressors or pumps. These mechanical devices are replaces directly by construction elements of buildings. Examples of simple photo-thermal solutions are presented in fig. 2.1.

In passive systems transport of radiation energy appears in three different ways:

- transfer through media,
- reflection from surfaces,
- absorption on the surface of solid bodies or adsorption in liquids.

In the conversion process, solar energy is transferred to the elements of constructions or to the interiors of buildings. Heat accumulated inside buildings escapes through exterior barriers, walls, windows or other thermal leakages. The amount of thermal losses depends mainly from temperatures difference, thickness of barriers or walls and thermal conductivity of materials [5, 8].

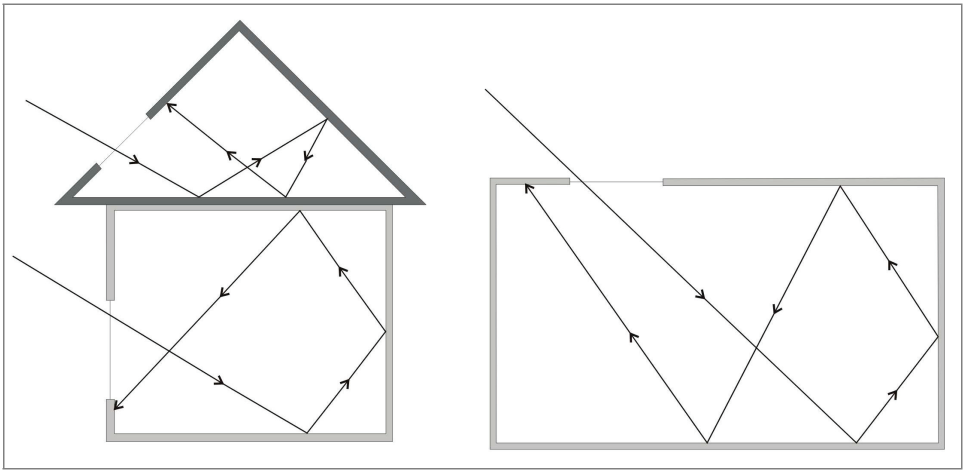

Fig. 2.1. Example of simple passive photo-thermal systems

Passive heating systems (PHS) of buildings enable to save up to 40% of thermal energy. These systems are cheap because extra investments are borne only at the stage of construction. Making only simple modifications, one can improve PHS by implementation:

- extra barriers or walls which additionally accumulate thermal energy,
- additional surfaces reflecting solar radiation and improving brightness of rooms,
- additional interior spaces or rooms accumulating thermal energy.

There are possible more complex solutions of passive heating systems which base on architectural ideas applied for system of buildings [2]. These concepts use additional constructions like built-up passages, interior courtyards etc. to store up extra solar energy. It is worth to mention that a quality of building materials plays an important role in such systems. The main items, which influence on the quality of system, are:

- proper level of isolation,
- type of window with special emphasis on thermal properties of window pane,
- type and quality of building materials apply in walls in order to improve accumulation of energy.

An interesting solution, which improves storage of energy, is Trombe wall (fig. 2.2). This is a sun-facing massive wall, which is separated from the outdoors by glazing and an air space. Its main goal is to absorb solar energy and releases it selectively towards the interior at night. Even simple pane glass works quite well for this process because glass is transparent to visible exterior light but limits inner escape of infrared radiation (heat).

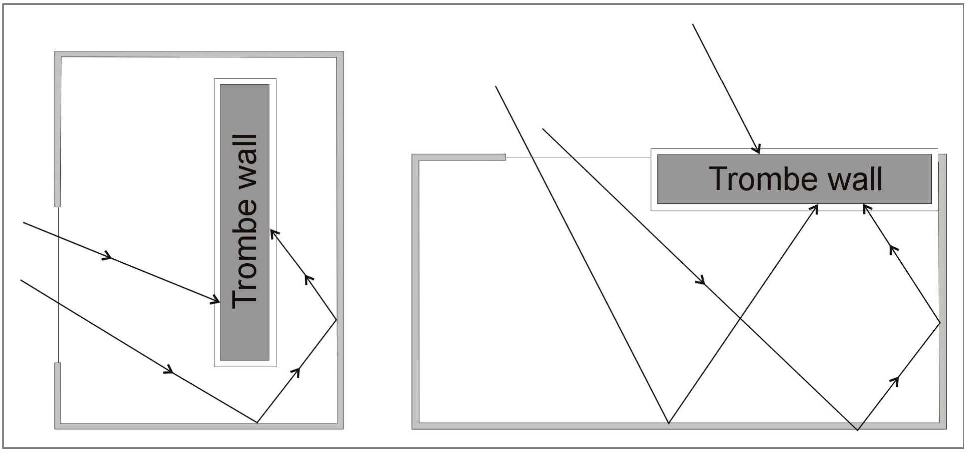

Fig. 2.2. Examples of Trombe walls

Properly acting PHS system requires also cooling solution, which protects against excessive acumination of solar energy during extremely sunny days and allows giving back surplus of energy at nights or during cloudy weather. Such function could fulfill for example water reservoirs where accumulation and transport of energy could be regulated by phase change of liquid. The main phase changes taking into account are: melting and evaporation and additionally dissolution for brines. Passive cooling solutions could also be divided into three groups [5]:

- direct passive cooling systems (DPCS),
- indirect passive cooling systems (InPCS),
- isolated passive cooling systems (IsPCS).

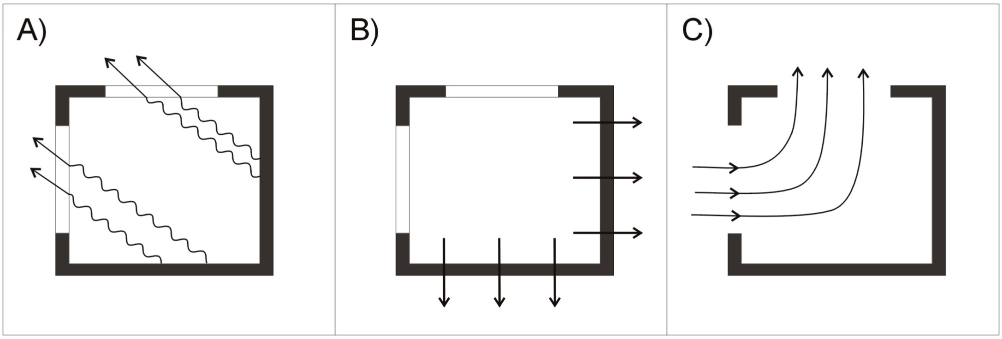

Fig. 2.3. Examples of DPCS systems using: A) radiation, B) conductivity, C) convection

All these systems base on the well-knows mechanisms of energy transportation: radiation, convection and conductivity. In case of DPCS system, regulation of energy flux occurs through windows or other transparent barriers, walls and free flow of air. The examples of all above-mentioned DPCS solutions are presented in fig. 2.3.

More complex but still simple in an implementation are InPCS systems. They require additional components (like e.g. massive obstacles, external or internal water reservoirs), which play a role of regulators and control temperature inside a room. The direction of energy transfer strictly depends on current thermal conditions. Efficiency of such solutions is related to a thermal capacity of applied elements. The cheapest applications base on massive blocks which accumulate surplus of heat during day cooling down an interior (fig. 2.4B). Much more interesting but requiring more efforts solution is connected with additional water reservoirs. They are mainly placed at the roofs of buildings like shown in fig. 2.4A) or between floors – fig. 2.4C) what significantly increases potential invest costs. The efficiency of such system depends not only on thermal capacity of the reservoir but also on an intensity of evaporation processes. Although these systems are thought as a self-regulation ones they require periodic control. Decrease of a quality of water causes by plants or solid pollutants has direct influence on working parameters of a whole system.

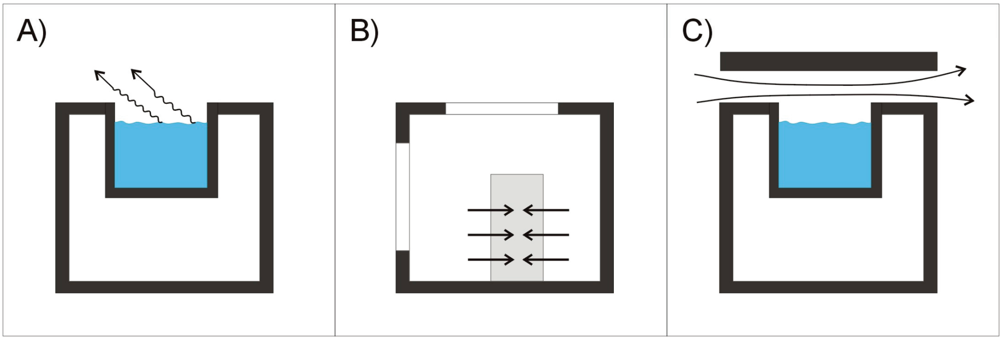

Fig. 2.4. Examples of InPCS systems using: A) radiation, B) conductivity, C) convection

Isolated passive cooling systems need some primitive control units. The examples of its utilizations are shown in fig. 2.5. These solutions require additional spare spaces like e.g. cellars or lofts, which are used to accumulate or take back surplus energy [5, 8].

As the simplest control unit one can use thermal-isolated baffles. The baffles separate the proper room (1) from spare working space (2). If they are closed there is no heat flax between these two spaces. Opened baffles allow transferring heat from space (1) to the other (2) cooling the first one (1). The spare rooms (2) could operate as InPCS or DPCS systems.

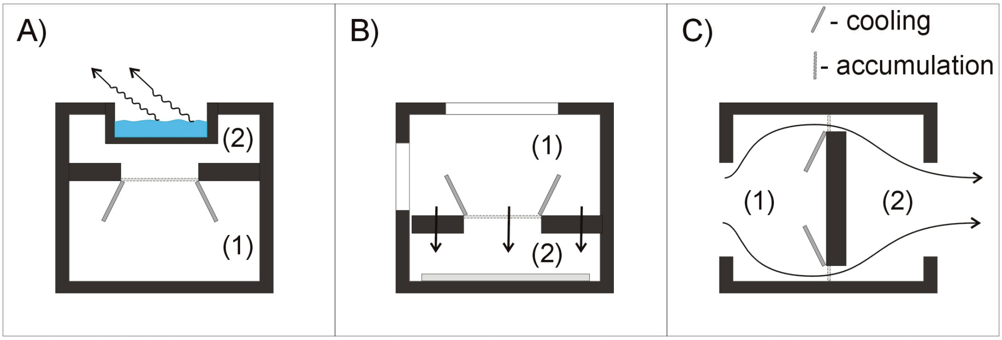

Fig. 2.5. Examples of IsPCS systems using: A) radiation, B) conductivity, C) convection

All above-described solutions could be combined together creating complex heating-cooling systems of buildings. Interesting examples of selected solutions are presented in fig. 2.6. It shows that even simple combination of the transparent barriers, massive obstacles or spare spaces can lead to the noteworthy systems which work effectively without any additional exploitation costs [2, 4, 5].

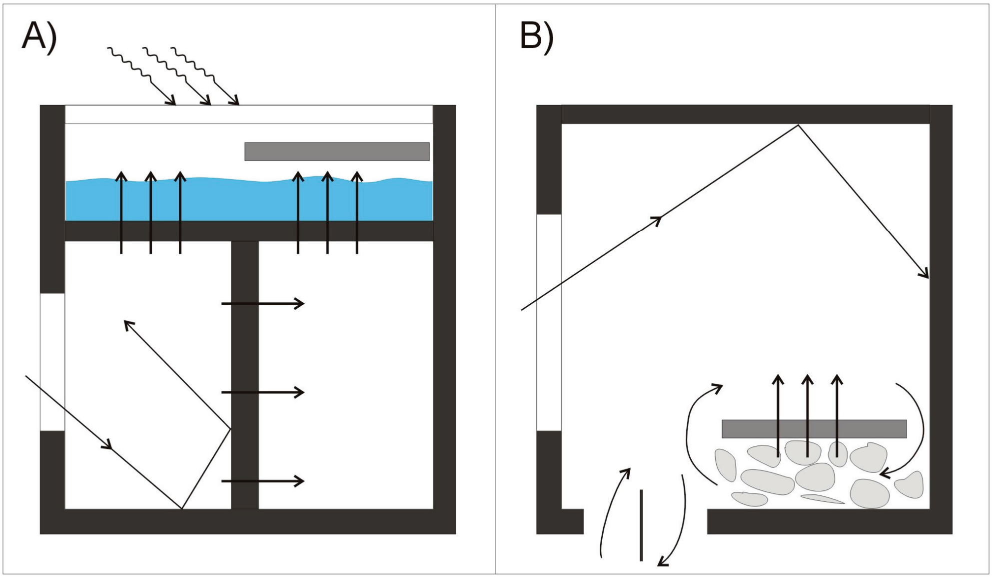

Fig. 2.6. Examples of combined heating-cooling systems

In figure 2.6A) the space is divided into three sections. The main room is placed next to the spare space, which accumulates heat. Above there is a water reservoir, which plays a role of indirect passive cooling system. Additionally between water and flat transparent window there is a massive obstacle, which could accumulate energy releases from the reservoir. In figure 2.6B) there is presented combination of massive obstacle and stack of stones with simple ventilation. The heat is stored in the obstacle and next transport to stones. Air flowing through the stack improves heat exchange and additionally influences on the uniform temperature distribution inside the room.

2.2. Active photo-thermal systems

Solar energy could be not only converting into heat but also to a mechanical or electrical energy. These systems are called active photo-thermal ones. They can be divided into three groups regarding the temperature of the working medium and the role, which these systems play in transfer of energy:

- low-temperature systems (e.g. solar collectors, solar ponds),
- high-temperature systems (e.g. solar farms, solar power plants),
- supported systems (e.g. heat stacks, heat pumps, thermal diodes).

2.2.1. Low-temperature active solar systems

One of the cheapest device, which is commonly used to convert solar energy, is solar collector [3–5]. Solar energy from collectors is mainly used for heating water or buildings. Solar collectors belong to low-temperature active solar systems where the insolation is absorbed by a fluid, usually air, water (brine) or glycol, which is moved by fan or pump (fig. 2.7).

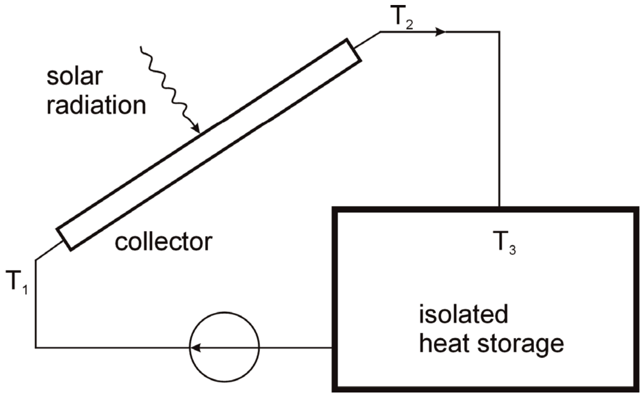

Fig. 2.7. Example of an active solar system
– a solar collector coupled to a isolated heat storage by pump

The working parameters of a solar collector depend on two main factors: a construction of the collector (e.g. properties of an absorbing surface, protection against losses of energy) and an orientation of a collector's surface [7]. An orientation of a collector's plane to the Earth's surface and the Sun could be described by three angles (fig. 2.8):

- Slope β – the angle between the collector's plane and the horizontal plane (for the surface faces towards the equator $0 < \beta < 90°$),
- Surface azimuth angle γ. Projected on the horizontal plane, γ is the angle between the normal to the surface and the local longitude meridian. For northern hemisphere γ is 0° for horizontal collector's surface or for collector's surface faces in the south direction,
- Angle of incidence ϑ. The angle between the solar beam and direction normal to the collector's surface.

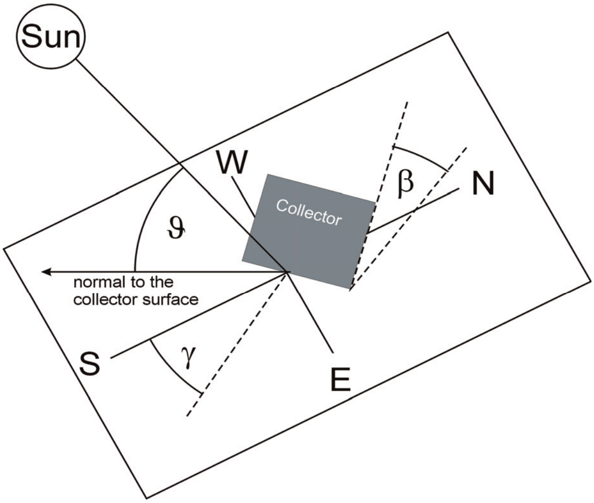

Fig. 2.8. An orientation of a collector's plane to the Earth's surface and the Sun

The optimization of the thermal efficiency of collectors is strictly connected with the selection of the best values of first two angles β and γ for given latitude and season (the ϑ angle depends on position of the Sun and changes during the year). An example of the solar collector's construction is presented in fig. 2.9. Crucial point for efficient collector's work is a selection of the material for a selective surface. The selective surface should maximise its energy gain and minimise its energy loss, by having a large monochromatic absorptance α and small monochromatic emittance ε [5].

Simple calculation allows estimate the net heat flow P_{net} into the collector's surface A:

$$P_{net} = \eta_{ce} A G, \tag{2.1}$$

where η_{ce} is the capture efficiency of the selective surface ($\eta_{ce} < 1$), A – exposed area of the collector, G – the irradiance on the collector. In fact only a part of P_{net} is transferred to the fluid flowing through the collector and the final output power P_u is equal:

$$P_u = \eta_{te} P_{net} = \dot{m} c (T_2 - T_1)\,, \tag{2.2}$$

where η_{te} is the transfer efficiency of the net heat flow P_{net} to the fluid, $\dot{m}$ – mass flow rate of the working medium through the collector's tubes, c – specific heat capacity of the working medium, T_2 and T_1 – temperatures of the fluid respectively at the inlet and outlet of the collector's tube.

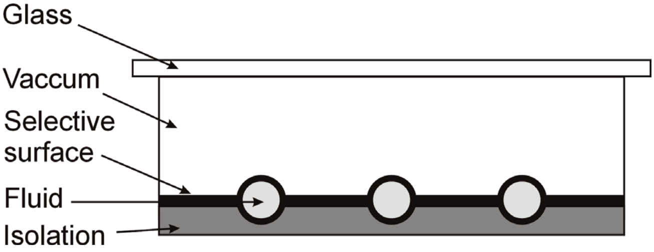

Fig. 2.9. An example of the solar collector's construction

In the regions where insolation is relatively high and constant through a whole year conversion of solar energy to heat is not so important as a production of electricity. Solar collectors are at this situation replaced by for example a solar pond – the other example of low-temperature active solar systems. Although both systems absorb solar energy, solar ponds do not transfer it to heat storage but accumulate in its volume. This effect is obtained by dint of the stratification of salt water maintained respectively by adding fresh water to the surface layer and salt to the accumulative layer at the bottom of the reservoir [1]. Warmed brine concentrates at the bottom of the pond and does not transfer heat to the surface by convection mechanism. An example of solar pond is presented in fig. 2.10 where one can distinguish several layers with different values of temperature and salt concentration.

Above presented reservoir consists of three zones: surface, no convection and accumulative one. In surface layer the salt concentration is minimal because of continuous flux of fresh water. The solar energy is absorbed by deepen layers and its transfer to the surface of pond is blocked by no convection layer with almost constant salt concentration. Heat accumulated in the bottom layer could be used by working medium (e.g. freon, ammonia) to drive turbogenerator, which works in Organic Rankine Cycle.

Typical depth of the solar pond is a few meters and in a moderate temperature climatic zone it is possible to obtain from it a power of order 5 W/m^2. Temperature at the accumulative zone is very stable and could be in the range of 85–100 °C during few weeks. The advantages of solar pond concentrate on its simple construction and lower energy losses having its power and efficiency even better than solar collectors. Disadvantages are connected with higher invest costs including area of the ponds and additional equipment necessary to keep it running (e.g. desalination installation, higher consumption of fresh water).

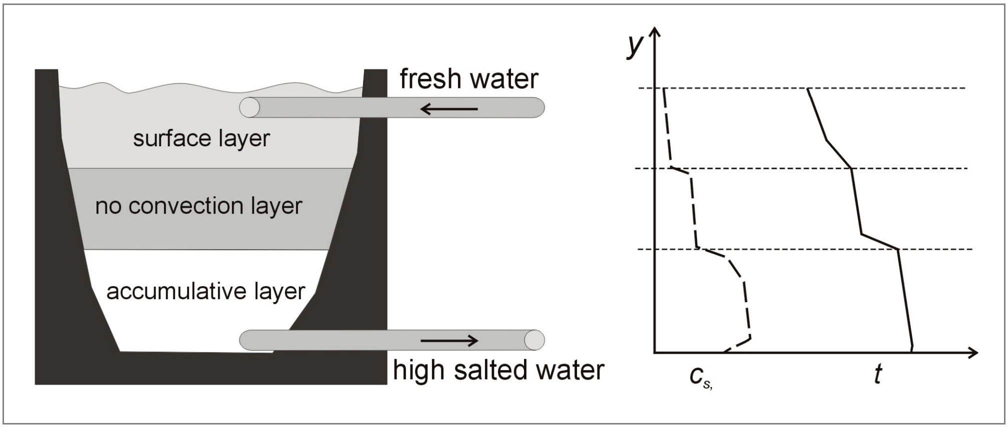

Fig. 2.10. An example of solar pond with salt concentration and temperature distributions

2.2.2. High-temperature active solar systems

An example of the high-temperature active solar systems is a turbine combined with a solar chimney [5, 6, 7]. The idea of solar chimney is very simple and bases on a forced convective motion of warm air. The Earth surface warmed by solar radiation heats up lower layers of the atmosphere causing its vertical motion. This phenomenon is called free convection and is often utilized by e.g. birds or gliders. In order to stabilize the convective motion and keep proper profile of its velocity turbine is placed in a specially designed structure called solar chimney (fig. 2.11). The cold air is going down and warms up near the ground. Next it is sucked to the interior of the chimney and driven up to the turbine. The cycle is very simple but also efficiency of electricity production at such constructions is at the level of a few percent. The best solar conditions for such structures are in Africa, Australia, America and Asia.

Experimental prototypes of solar chimneys have height about two hundred meters and diameter up to thirty meters. Its power is about ~50 kW. The professional chimneys will have height up to 1 kilometer and diameter about 150 m. Its power is estimated on 200 MW. These buildings will scoop the air from the area, which radius will be approximately 2 km and the mean velocity inside the chimney will be about 15 m/s [5].

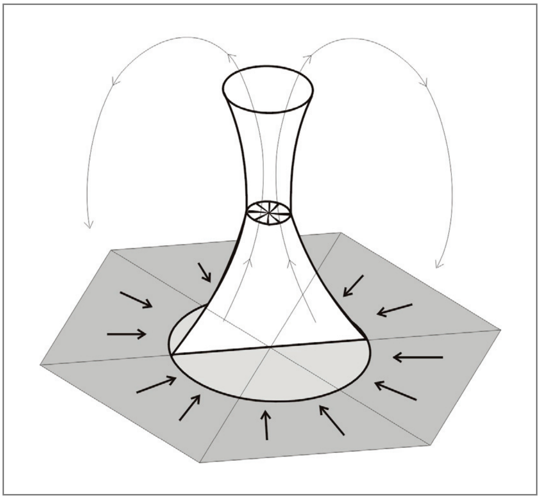

Fig. 2.11. An example of solar chimney with
a turbine together with a scheme of air circulation

2.2.3. Supported systems

Under the name “supported systems” we understand systems, which indirectly utilize solar energy [2, 5, 7]. Usually its use the heat that was earlier gained from solar radiation and accumulated in a ground, water, air or other heat stack. One of the simple examples of such device is a heat pump. An idea of a heat pump is to transport heat from a lower (colder) heat source (e.g. air, water or ground, industrial waste heat or ventilation air extracted from building) to an upper (warmer) one (e.g. interior of building). This transfer is realized in a forced thermodynamic cycle driven by electrical engine (compressor) or by additional heat flux (absorption pump, heat transformer etc.). In figure 2.12 there is presented a scheme of an electric-motor-driven vapour compression heat pump. The main components of the heat pump are two heat exchangers (condenser and evaporator), a compressor and an expansion valve. A volatile fluid, called refrigerant, circulates in the system according to the Linde thermodynamic cycle shown in fig. 2.12B. Working fluid is compressed to the higher pressure and temperature by a compressor (1–2 line in the fig. 2.12B) and is driven to a condenser. In the condenser, refrigerant condensates under constant pressure p and temperature T (2–3 line). During this process the latent heat Q_U is transfer to the upper heat source. Next, working liquid is expanded in an expansion valve to the state of two-phase mixture (3–4 line) and is driven to an evaporator. In the evaporator, the heat from lower heat source is transfer to the refrigerant causing its evaporation (4–1 line). The vapour flows towards the compressor and this finishes one vapour compression cycle.

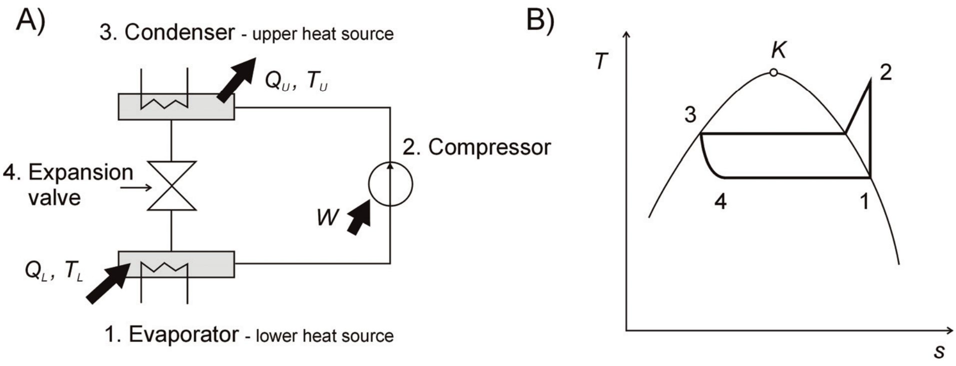

Fig. 2.12. A) Scheme of a closed cycle, vapour compression heat pump,
B) thermodynamic cycle of a presented heat pump (Linde cycle)

Knowing that the upper heat source has the temperature lower than the refrigerant in the condenser and that the lower heat source has the temperature higher than two-phase mixture in the evaporator one can easily calculate a coefficient of heat pump efficiency:

$$\varepsilon = \frac{Q_U}{W} = \frac{Q_L + W}{W}, \tag{2.3}$$

where W – external energy provided to the compressor. As it can be seen, the efficiency of the heat pump strongly depends not only from the properties of the refrigerant but also from the both temperatures of the upper and lower heat sources.

Selection of the proper heat source is a crucial factor determining further efficiency of the device. Several possible heat sources are listed below:

– Ambient air – typical temperature range from –10 °C to 15 °C. It is the most common heat source but an efficiency of air-source heat pump is 10–30% lower than e.g. water-source pumps.
– Exhaust air – typical temperature range from 15 °C to 25 °C.
– Ground water – typical temperature range from 4 °C to 10 °C. In open systems water is pumped up, cooled down in an evaporator and after that it returns to the ground.
– River and lake water – typical temperature range from 0 °C to 10 °C. These systems work similarly to the open ground-water systems.
– Ground-source systems – typical temperature range from 0 °C to 10 °C. Very popular solution in many domestic and industrial systems. Heat is extracted from the pipes lying horizontally or vertically in the soil, that causes the decrease of the ground temperature especially during the winter.
– Seawater – typical temperature range from 3 °C to 8 °C. Almost perfect lower heat source specially when is used in a large-size heat pump installation.

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Chapter 3

Biomass gasification in European Union

Gasification of biomass converts solid renewable fuel to gas that can be used in a modern conversion device, such as a gas turbine or engine, for electricity and heat production (see figure 3.1). This opens the possibility of moving from the traditional, small-scale, low-efficiency steam cycle to a combined steam and gas turbine with higher efficiency. Many studies have revealed the advantages of gasification over combustion for power and heat production [1].

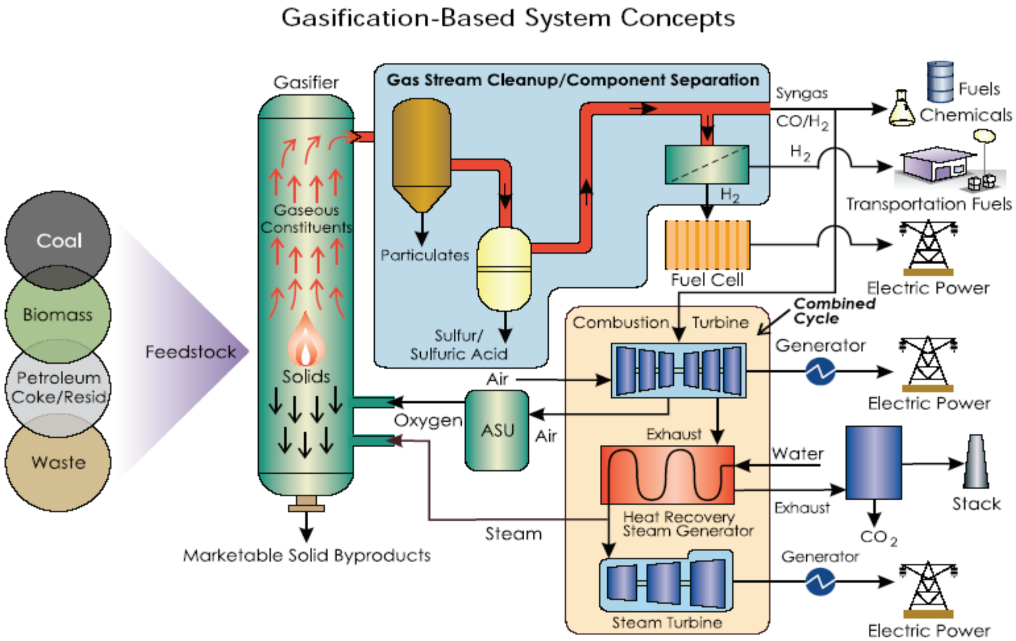

Fig. 3.1. Integral gasification concept

The advantages can be summarized as follows:

- high efficiency for electricity production with a gas turbine or engine, even at a small scale;
- good prospects for use in CHP, because of the small scale;
- cost-effective reduction of emission due to the small gas flows, compared to combustion.

3.1. Research and development focuses on gas cleaning

A number of universities, research institutes and industries are active in the development of gasification technologies. The research focuses on the development of the gasifier itself (2 and 3 stages), a better understanding of the gasification process for different kind of fuels, and the cleaning of the gas coming out of the gasifier. The gasification process can result in different qualities of gases, with low or medium heating value compared to natural gas.

Different types of gas-cleaning processes have been developed and tested; conversion or removal of the tars in the gas is required for its application in gas turbines and engines. Ammonia has to be removed, due to NO_x emission constraints. Many countries are undertaking active R&D to overcome these hurdles – for instance, in Sweden (TPS) and in the Netherlands (ECN and BTG) have developed specific tar conversion units. Almost ten years of intensive R&D work in Harboore has ultimately resulted in a successful demonstration plant. At present, the wet gas cleaning has proven its effectiveness, and research is conducted on cleaning of the wastewater. Biomass gasification sees several applications in several market segments, the results of which are discussed in more detail below [2].

3.2. Implementation and demonstration in the EU

Heat gasifiers are commercially available. The most well-known technologies are those of **Bioneer** (fixed-bed, updraft), **PRM Energy** (fixed-bed, updraft), **Ahlstrom** (now Foster Wheeler) and **Lurgi Umwelt** (both CFB). Less known are small scale heat gasifiers installed in several developing countries supplying heat for lime kilns, tea drying [4].

About ten Bioneer gasifiers have been successfully in operation for a number of years in Finland and Sweden. In most cases the gas is used for combustion in boilers and district heating purposes. Bioneer is now marketed by Condens Oy, Finland.

PRM Energy Systems has 18 units operating on four (soon to be five) continents gasifying 500 000 tons annually of biomass, mostly rice husk. Usually, the heat is used for industrial drying applications or low pressure saturated steam for an industrial process.

The first commercial fluid bed gasifiers were installed by Ahlstrom, Finland in the middle of 1980's. Those "Pyroflow" circulating fluid bed gasifiers had a capacity of 15–35 MW_t. The product gas from these gasifiers is used for fueling lime-reburning kilns of pulp factories. Four are still in operation.

The first Lurgi circulating fluidised bed (CFB) gasifier was built in 1987 in Pöls, Austria by a large paper mill; the heat was used in the lime kiln. Since 1996 a CFB gasifier plant of Lurgi Umwelt has been in operation at the Rüderdorfer Zement GmbH, Germany.

In autumn 2001 a 40 MW_t heat gasifier was taken in commercial operation for energy production and aluminium recovery in Varkaus, Finland, based on Foster Wheeler technology.

Cofiring gas from a gasifier in existing power plants

The first gasifier was installed in Zeltweg, Austria, followed by others in Lahti, Finland, Amer, the Netherlands, Vermont, in the USA and Ruien, Belgium. Despite successful operation, the plant in Austria was closed because the power station was shut-down.

Table 3.1. Cofiring gasifiers

Location	Plant	Capacity MW_t	Status
Zeltweg, Austria	CFB, directly fed into Pulverised Coal boiler	10	Operational since 1998 and shut-down in 2001
Lahti, Finland	CFB, Foster Wheeler, directly fed into Pcoal boiler	60	Operational since 1998, upgrading gas cleaning
Amer, Netherlands	CFB, Lurgi, with gas cleaning and ammonia removal, into PC boiler	80	Start-up since 2000, gas cleaning modified in 2004
Vermont, USA	Ferco Silvagas (Batelle) gasifier, planned to install CC	60	First test runs in 2000, demonstration project finished
Ruien, Belgium	CFB, Foster Wheeler, directly fed into Pcoal boiler	50	Operational since May 2003
Energi E2 A/S	CFB on straw	100	Not realised yet
Lyngby, DTU, Denmark	Danish Fluid Bed Technology. Low Temperature Circulating Fluid bed on woody, agricultural and waste fuels	0.5	Commissioning is planned for autumn 2004

The Vermont demonstration project has been successfully completed, but not in operation at present because of the low availability of the powerplant. The tests have shown that the gas quality was good enough to operate in a gas turbine. The Lahti gasifier is in full operation.

A new similar type of gasifier became operational in Ruien, Belgium. The gas cleaning section of the Amer plant is being modified and tested and will become operational in 2005. The Danish Fluid Bed Technology Aps is testing and developing the Low Temperature Circulating Fluid bed (LT-CFB) for cofiring.

The design allows using not only wood fuels but also very difficult agricultural and waste fuels. The 2nd generation 10 times up-scaled test plant was built at DTU and commissioning was in 2005.

IGCC – Integrated gasification combined cycle

IGCC is seen as the total final concept of a biomass-to-electricity system. The development and implementation, however, is complex, as it involves all components, from fuel to power, in the gasification system. The European Commission has identified the potential of this technology, and called for proposals for Targeted Projects on this subject in 1993. Three projects were selected, **Arbre, Bioflow and Bioelettrica** [5]. Arbre is being realized and the CC has been in operation. The selected atmospheric gasification technology of Lurgi was changed to the pressurized gasification technology of Carbona, but the project was definitely terminated in 2003.

The cofiring project in Vermont is seen as a development towards an IGCC plant. Ferco is in negotiation with different clients to demonstrate the IGCC technology. Previously Sydkraft, a private company in Sweden, started a similar development in 1992 and tested it successfully, but did not see commercial potential due to the low electricity prices in Sweden and mothballed the plant in 2000. The Värnamo pressurized gasifier of Foster Wheeler (formerly Ahlström) was also mothballed after positive results of the demonstration project. The capacity was too small for commercial operation. Within the sixth EU framework program, a new project has been recently approved for syngas production using the Värnamo gasifier. It is an integrated project called CHRISGAS.

Table 3.2. IGCC plants

Location	Plant	Capacity MW_e	Status
Vänamo, Sweden	Pressurized CFB, Foster Wheeler	7	Mothballed
Chianti, Italy	CFB gasifier, TPS, RDF fuel	6.7	Operational
Arbre, Yorkshire, UK	CFB, with tar cracker, TPS	9	Cancelled
Bioelettrica, Italy	Pressurized CFB, Lurgi	8	Cancelled
SVZ, Schwarze Pumpe	Fixed bed, BGL, entrained flow		Operational

CFB with gas engine

A relatively new application is the combination of circulating fluid bed technology coupled with gas engines. Table 3.3 shows examples of this combination.

Table 3.3. CFB gasifiers with gas engines

Location	Plant	Capacity MW_e	Status
Güssing, Austria	Fast internal circulating fluidized bed	2	Operational on gas engine, more than 9500 hrs
Skive, Denmark	Carbona CFB, catalysis gas cleaning and engine	4	Under commissioning

Fixed bed gasification for power production

A great number of small-scale, fixed bed gasifiers are either in operation or under development around the world. Some of these are based on old technologies (N-Ireland, Harboore) but also recent successful R&D results have been implemented (ESP, tar crackers, 2-stage gasifiers, etc.). Most of the units are CHP plants where heat is used for district heating. In India and China alone, hundreds of gasifiers are in operation at farms and small industries to produce heat or electricity at a local level. Other countries have successful demonstrations of small fixed bed gasifiers, with the success defined here as at least 1000 hours of operation a year for power production. Table 3.4 tries to give an overview of operational systems.

Table 3.4. Status of fixed bed gasifiers for power production (2005)

Location	System, supplier	Power MW_e	Status
1	2	3	4
Harboore, Denmark	Babcock & Wilcox, Volund updraft, CHP with gascleaning and 2 gas engines	1.5	Commercial
Seco-Bois, Belgium	Xylowatt sa, downdraft CHP	0.6	Under commissioning
Gedinne, Belgium	Xylowatt sa, downdraft CHP, wood chips	0.6	Under commissioning
Greasted, Denmark	BioSynergi, open core, wood chips	0.075	Under commissioning

Table 3.4 continued

1	2	3	4
Viking gasifier, DTU, Denmark	2-stage developed at DTU used for long-term testing	0.017	Operational since June 2002, scaling-up foreseen
Austria	Grübl, wood gasifiers	0.05	Two in operation at farms
Londonderry, Northern Ireland	Rural Generation, downdraft on farm, runs partially on energy crops	0.1	In operation, 16.000 hrs operating
Blackwater Valley Museum, N-Ireland	Exus Energy, downdraft on farm, runs partially on energy crops	0.2	In operation, 1.000 hrs operating
Ballymena ECOS	Biomass Engineering, downdraft	0.075	In operation, 2.500 hrs
Spiez, Switzerland	Pyroforce gasifier	0.2	Operational since 2002
Bulle, Switzerland	Xylowatt, open-top	0.2	Operational since June
Beddington Zed, UK	Exus Energy, downdraft	0.13	Under commissioning
Legnano, Italy	CCT, downdraft and updraft	0.5	Under commissioning
Rossano, Italy	PRM, updraft, olive pits	4.5	Under commissioning

Entrained flow gasification for syngas production

The European Directive on liquid biofuels for the transportation sector has been an important drive to develop new technologies for syngas production using entrained flow gasification. In Freiberg, Germany, three entrained flow gasifiers are in operation for syngas, methanol, hydrogen and Fisher Trops diesel production from biomass. Pyrolysis oil gasification is also considered as an alternative route for this purpose.

Carbo-V is operating a 1 MW_t entrained flow gasifier at atmospheric conditions. Choren is marketing the technology. The engine operated for >500 hours, and in May 2003 the first methanol and Fischer-Tropsch diesel was produced. Recently a 35 MW entrained flow gasifier has been constructed in Freiberg. Future Energy GmbH is a new company, which bought the knowledge from BBP, Backcock Borsig Power (ex. Noell-KRC, ex-Deutsches-Brennstoff-Institut). They operate a 5 MW_t pressurised entrained flow gasifier. Future Energy is conducting the basic engineering for a new plant in the Czech Republic. The third entrained flow gasifier is in operation at Freiberg Technical University.

Other commercially operated entrained flow gasifiers are installed at SVZ Schwarze Pumpe, Germany and BASF, Seal Sands, UK.

3.3. Examples of the biomass gasification technology

Figure 3.2. and table 3.5. give an overview of existing “commercial” gasifiers in Sweden (2005).

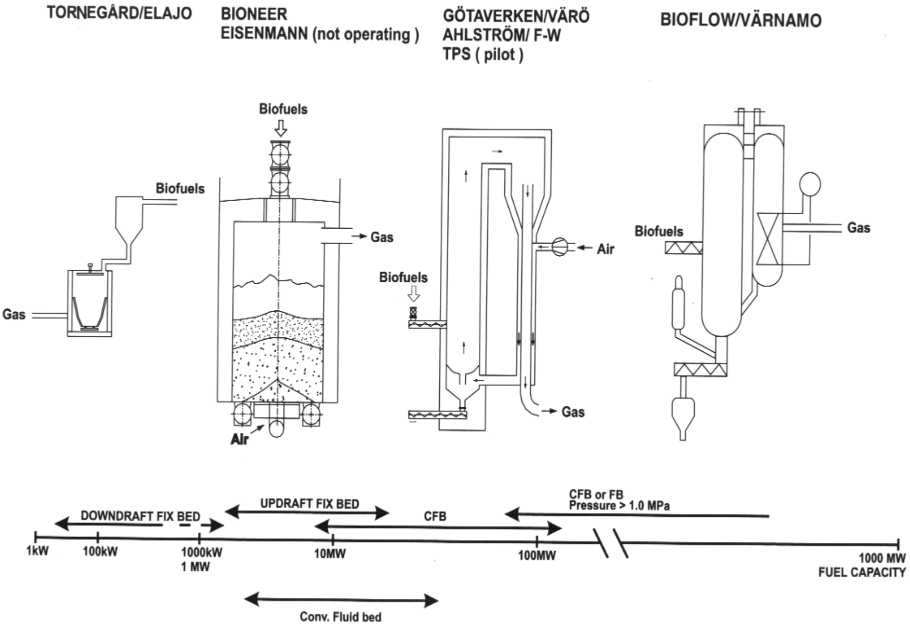

Fig. 3.2. Commercial biomass gasifiers in Sweden

Table 3.5. Commercial gasifiers in Sweden (1985–2005)

Process	Location	Type	Size (MW fuel)	Fuel	Commissioned date
Komako	Filipstad	DD	2	green chips	1986–1990
WGE	Oskarshamn	DD	2	RDF, pellets, wood	
Eisenmann	Rättvik	UD	6.5	chips, rubber, peat	1986–1990
Bioneer	Lid	UD	10 (6 + 4)	wood chips	1986
Bioneer	Vilhemina	UD	5	sod peat	1986
Foster Wheeler	Norrsundet	CFB	20	bark/wood chips	1983
Foster Wheeler	Karlsborg	CFB	25	bark/wood chips	1985
Kværner	Värö	CFB	35	bark/wood chips	1987
BIOFLOW	Värnamo	PCFB	18	wood chips	1994-96
Kværner	Frövifors	EF	4	black liquor	1993
Chemrec	Piteå	EF	0.5	black liquor	–

DD = downdraft reactor, UD = updraft reactor, EF = entrained flow reactor, n.o. = not in operation.

Updraft gasifiers

Successful updraft gasifier is the “Bioneer” from Finland (fig. 3.3 and tab. 3.5). The Bioneer gasifier installations have been running well on both peat and wood chips, despite some problems, e.g., with feeding and varying gas quality. The feeder hopper design has been changed in one of the plants. The major emission problem is NOx with fuels such as peat with a high nitrogen content (250–350 mg/MJ).

CFB gasifiers

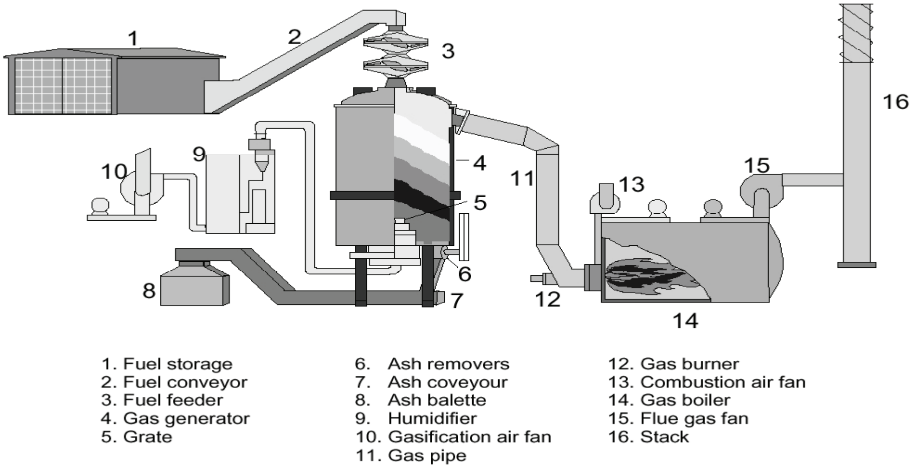

Fig. 3.3. Bioneer updraft gasifier

The CFB lime kiln gasifiers sold in Sweden were ordered before 1986 when the oil price was high, and ash enrichment in the black liquor recovery cycle was a problem at the powder combustion plant at ASSI, Piteå, Sweden. The three plants, two from Foster Wheeler and one from Kværner (tab. 3.3), are still in continuous operation.

Värö plant

The Värö gasifier plant was delivered by Kværner and commissioned in 1987. The plant includes a rotary drum dryer, fuelled by biogas, and fuel pre-treatment (fig. 3.4).

Crushing of the fuel, both of bark and wood waste, takes place in a primary and a secondary hammer mill to achieve the fuel size specification necessary for the gasifier. The feed system consists of two pressurised rotary feeders enabling gasifier pressure balance with cooled transport screws to the gasifier.

The gasifier is a refractory-lined free-standing vessel with solids recycling (fig. 3.5) and air/gas heat exchange. The product gas is piped to the dryer furnace and the lime kiln controlled by valves.

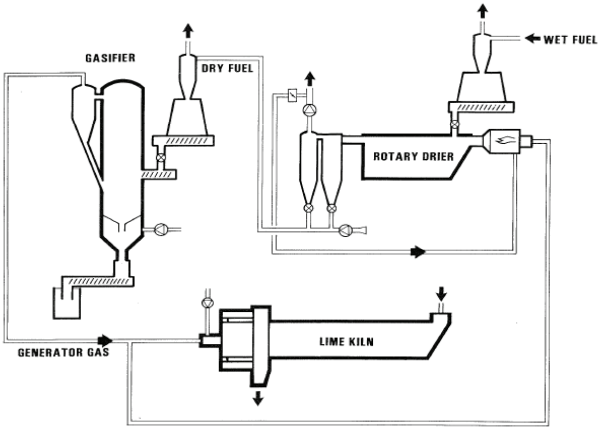

Fig. 3.4. Biomass gasification plant at Värö Mill

Fig. 3.5. Värö gasifier

The BIOFLOW (Sydkraft/Foster Wheeler) concept in Värnamo

Sydkraft AB built the world's first complete IGCC power plant which utilises wood as fuel. The plant is located at Värnamo, Sweden, and the technology used is based on gasification in a pressurised CFB. The gasification technology was developed in co-operation between Sydkraft and Foster Wheeler Energy International Inc. The plant can be operated as a co-generation plant and is cooled by a district heating system or by separate air coolers. The Värnamo plant (6 MW_e/9 MW_t) was constructed during 1991–1993, operated 1993–1999 and was an important step forward in developing highly efficient and environmentally acceptable technologies based on biomass. The dried and crushed wood fuel is pressurised in a lock hopper system to a level determined by the pressure ratio of the gas turbine, and fed by screw feeders into the gasifier a few metres above the bottom. The operating temperature of the gasifier is 950–1000 °C and the pressure is approximately 1.8 MPa. The gasifier is a CFB and consists of the gasifier itself, cyclone and cyclone return leg. All these three parts are fully refractory-lined. The gasifier is air-blown. About 10% of the air in the gas turbine compressor is extracted, next compressed in the booster compressor, and then injected into the bottom of the gasifier. The gas produced is burned in the combustion chambers and expands through the gas turbine, generating 4.2 MW_e. The gas turbine is a single-shaft industrial unit. The fuel supply system, fuel injectors and the combustors were redesigned to suit the low heating value gas (5 MJ/m^3). The hot flue gas from the gas turbine is ducted to the heat recovery steam generator (HRSG), where the steam is generated, tohether with the steam from the gas cooler, is superheated and then supplied to the steam turbine (4 MPa, 455 °C), generating 1.8 MW_e. A simplified process diagram and the components of the gasification plant are shown in fig. 3.6. and tab. 3.6.

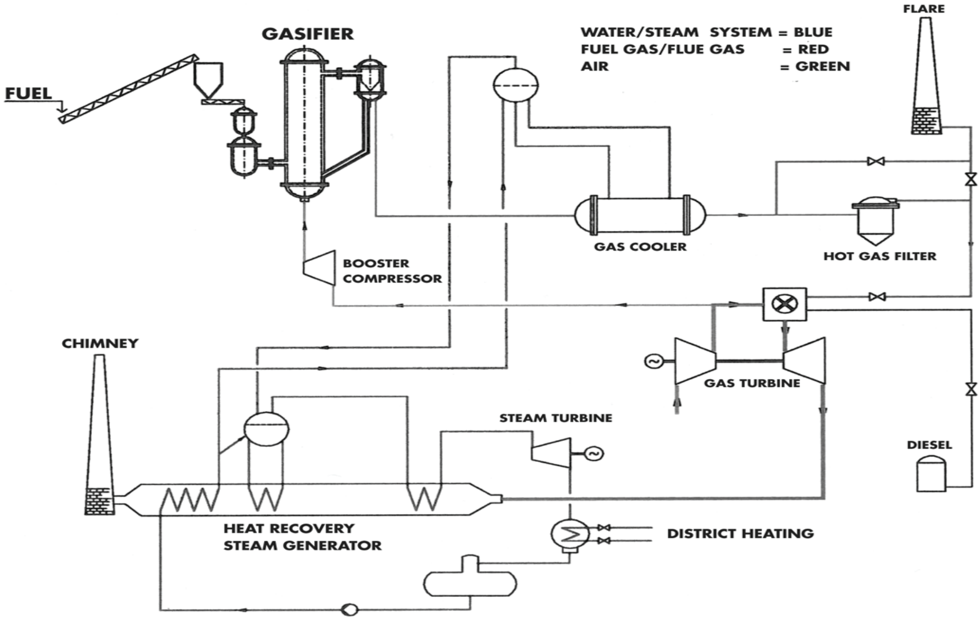

Fig. 3.6. Process diagram of Värnamo plant

Table 3.6. Technical data of the Värnamo plant

Power/heat generation	6 MW_e/9 MW_t
Fuel input	18 MW fuel (85% ds)
Fuel	Wood chips (Several other fuels have been tested with good results.)
Net electrical efficiency (LCV)	32%
Total net efficiency (LCV)	83%
Gasification pressure/temperature	1.8 MPa/950 ºC
Lower calorific value of product gas	5 MJ/Nm^3
Steam pressure/temperature	40 MPa/455 ºC
Plant owner	Sydkraft AB

The TPS/Ansaldo RDF Gasification Process – Grève-in-Chianti plant

Since the mid-1980s, TPS has worked on the development of an atmospheric-pressure gasification process. The initial driving force for such development was the possibility of fuelling a lime kiln with biomass-derived gas. The total process layout (fig. 3.7) was designed by Tavolini s.r.o and built by Ansaldo Aerimpianti.

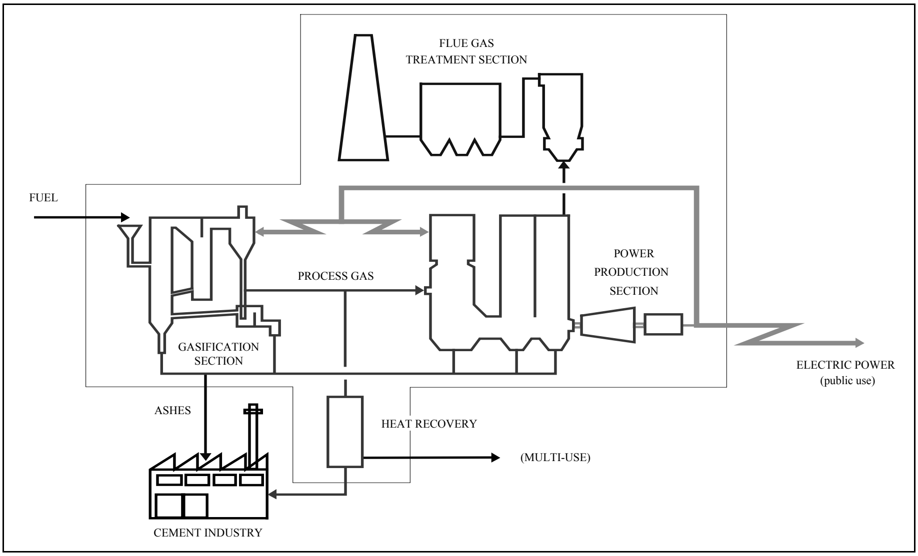

Fig. 3.7. Process scheme of TPS/Ansaldo RDF gasification plant in Grève-in-Chianti

RDF fuel is delivered to the plant in a pelletised form. The pellets are fed into the lower sections of the two CFB gasifiers, each of 15 MW fuel capacity. The gasifiers operate at close to atmospheric pressure and at the temperature of approximately 850 °C, employing air as the gasification/fluidising agent. A part of the air is injected into the gasifier vessel through the bottom section, the remainder is injected into the upper part of vessel. The raw gas from each gasifier passes through two stages of solids separation before being fed to the furnace/boiler. Alternatively, a part of this raw gas stream can be led to a nearby cement factory to be used as fuel in the cement kilns. The gas heating value is high, averaging 8 MJ/Nm^3.

The flue gas which leaves the boiler is cleaned in a Research-Cottrell three-stage dry scrubber system before being exhausted through the stack. The steam produced in the boiler drives a 6.7 MW$_e$ steam condensing turbine. Due to local restrictions, no flaring of the gas is permitted.

The TPS gasification and hot gas cleaning process – incl. ARBRE plant

During the latter part of the 1980s, TPS worked on the development of a hot gas cleaning process for application to biomass and waste-derived gases based on the use of dolomite as a tar cracking catalyst and absorbent for chloride. This hot gas cleaning technology was first demonstrated over long operational periods at pilot scale in the late 1980s, the gas was fired successfully in a dual-fuel engine. At that time, it was thought that a sizeable market existed in Sweden for the commercial application of TPS's gasification/hot gas cleaning technology to small-scale electricity production plants (say 5 to 20 MW_e). Although TPS did not succeed in selling any small-scale plants based on this gasification/hot gas cleaning technology, TPS continued to develop this application for IGCC systems and were successful in having its technology selected for several important projects aimed at proving the technical and commercial viability of biomass-fuelled IGCC systems (see below).

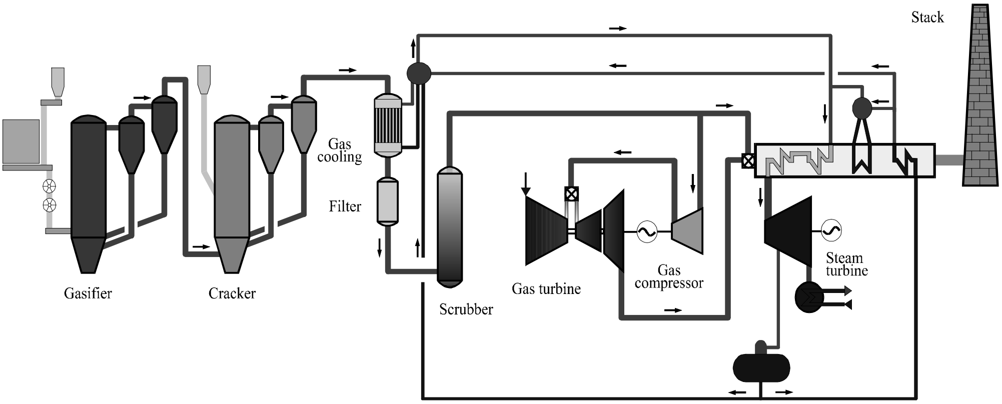

Fig. 3.8. TPS CFBG integrated gasification combined-cycle process scheme

According to TPS, there are three main applications for cold tar-free biomass--derived gas for electricity production:

1) firing of the gas in a furnace/boiler without further flue gas cleaning,
2) firing of the gas in a gas engine/dual-fuel engine,
3) firing of the gas in an IGCC system (fig. 3.8).

The TPS process is described in detail later in the section on the IGCC plant installed in Yorkshire, England (i.e. the so-called ARBRE plant), and is typical of the gasification/gas cleaning technology developed by TPS.

Project ARBRE- the United Kingdom

In 1993, the EU agreed to part-finance the construction of at least two short rotation coppice-fuelled combined-cycle plants in Europe, each of 8 to 12 MW_e capacity, including Project ARBRE in the UK. Figure 3.9. shows a simplified process flow diagram of the plant.

In December 1995, ARBRE Energy Limited (AEL), as the majority owner Yorkshire water plc, later to be renamed Kelda plc, was formed to implement the generating plant based on the following understanding of the role of AEL:

- to contract local farmers to cultivate, harvest and transport short rotation coppice (SRC) to the generating plant,
- to contract fuel suppliers to deliver forestry residues to the generating plant,
- AEL to award a turnkey contract to a third party for design, construction, commissioning and AEL to award 15 year O&M contract to a third party,
- AEL to award 15 year O&M contract to a third party.

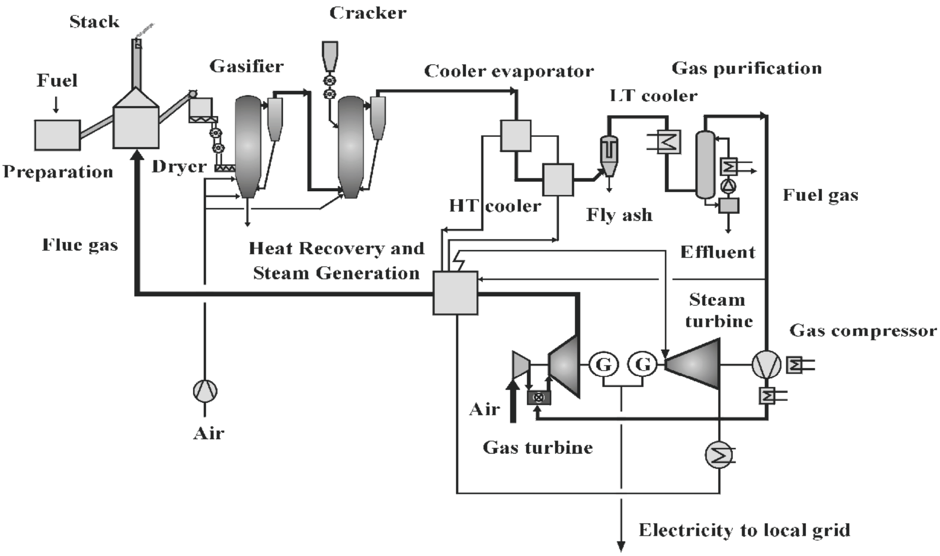

Fig. 3.9. Project ARBRE process flow scheme

The plant was able to consume 43 000 dry tonnes of wood per year and its net electrical efficiency was projected to be ca. 30%. This relatively low efficiency was the result of the requirement of eligibility for the EU grant that net generation must reach 8 MW_e. After selecting the technically proven Typhoon gas turbine of 4.5 MW that could only be achieved by increasing the contribution of the steam turbine cycle to the overall output by firing the third gas produced directly into the HRSG [7].

CHEMREC

The Chemrec company was formed from the earlier SKF Plasma team. Earlier, it was a part of the Kværner group but today it is privately owned.

The gasification-based recovery systems are more flexible, and cooking liquor compositions ranging from sulphur saturated to low sulphidity or even sulphide-free liquor may be obtained in quantities suitable for use in bleaching operations or for sulphur-modified cooking.

Table 3.7. CHEMREC^{TM} vs. recovery boiler energy flows co-generation

	Modern recovery boiler	CHEMREC IGCC
Electricity	12%	24%
Steam	54%	53%
Losses	34%	23%

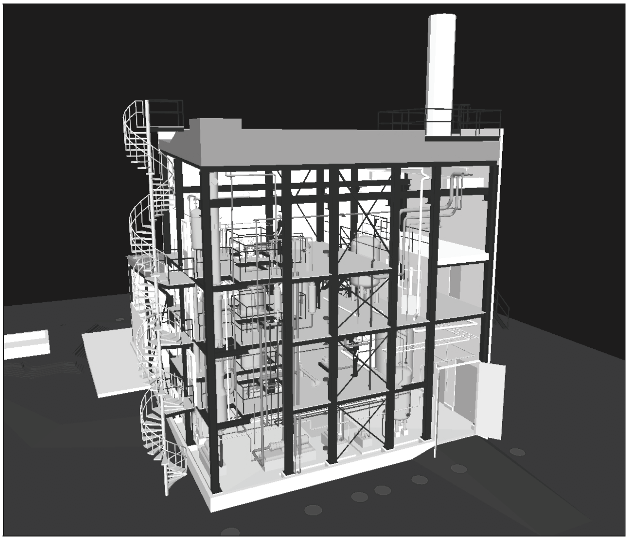

Fig. 3.10. CHEMREC^{TM} black liquor gasifier

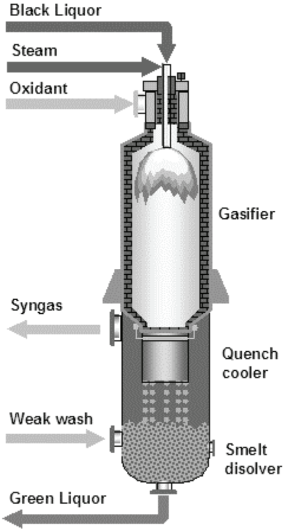

Fig. 3.11. Pressurised pilot plant DP-1 at ETC

Table 3.8. CHEMREC™ development

Plant	Capacity	Location	Date
Atmospheric pilot plant	3 tds/day	SKF, Hofors	1987–1990
Booster demonstration plant	75 tds/day	AssiDomän, Frövifors	1992–
Pressurised air-blown pilot plant	6 tds/day	STORA, Karlstad	1994–
Commercial Booster plant	300 tds/day	Weyerhaeuser, New Bern, USA	1996–
Pressurised pilot plant	2.4 tds/day	ETC, Piteå	2004
Financing and engineering, pressurised demonstration plant	?	AssiDomän, Piteå	pending

The core of Chemrec Kraft Recovery is the Chemrec gasifier – a refractory-lined entrained bed reactor in which concentrated black liquor is gasified under reducing conditions at around 900 °C (fig. 3.10). The liquor is decomposed in the reaction zone into melt droplets consisting of sodium compounds, and a combustible gas containing H_2 and CO. Emerging recovery technologies based on gasification and energy recovery in advanced gas turbine cycles promise substantial improvements in energy and environmental performance. Apart from a higher power to heat ratio, the CHEMREC–IGCC system (tabs. 3.7, 3.8 and fig. 3.12) has a higher thermal efficiency relative to a recovery boiler/steam cycle. This has a beneficial impact not only on emissions but also on the supply of steam and power to the mill.

Scanarc/Pyroarc (plasma) process

The Plasma Gasification technique evolved from the metallurgical process developments by SKF Steel in Sweden. In attempts to produce reducing gas for iron manufacture, plasma was introduced in the bottom of the shaft producing H_2 and CO from coal and air. The effectiveness of the plasma in this application was high, leading to a number of proposed processes.

The ScanArc (former “SKF Plasma”) process is a fixed bed, high temperature process producing a molten slag. The gasification is carried out in the updraft shaft. Differences in relation to other processes lie in the means to achieve the high temperature and in the cleaning of the raw gas. In the ScanArc process, the gas cleaning is achieved in plasma where the gas is heated to very high temperatures, causing decomposition of tar, chlorinated hydrocarbons and ammonia.

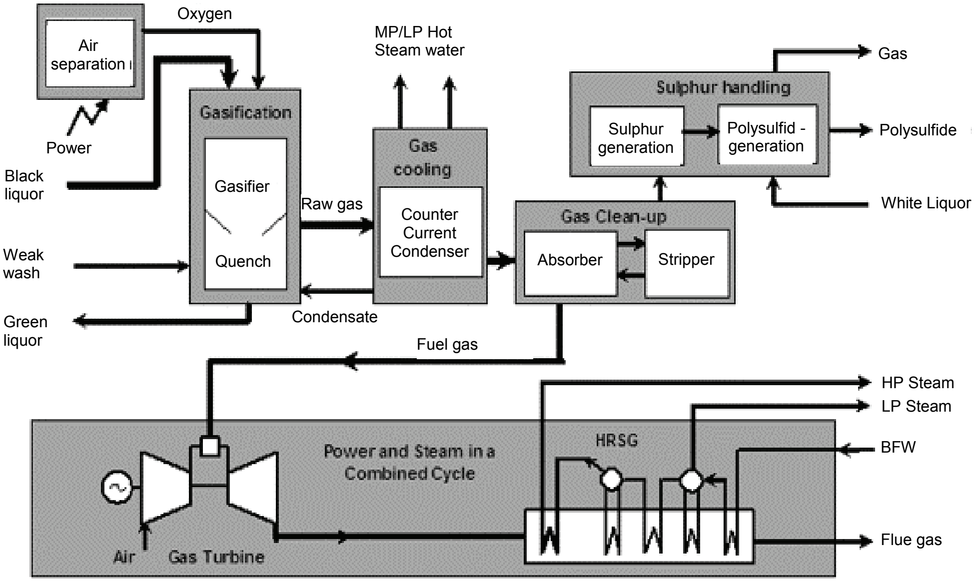

Fig. 3.12. The CHEMREC^{TM} steam/power cycle

The ScanArc process uses a shaft reactor and is fed in the middle with a mixture of air and oxygen. Oxygen is needed when the effective heat content of the wastes is too low to achieve the temperature of 1200 °C or more. For fuels for a reactor with heat contents above 10–15 MJ/kg, this does not constitute a problem. These heat contents are, however, not always met with MSW unless other wastes are added.

The raw gas is fed to the second reactor, which is more or less an empty shaft with a plasma generator on top. The electric plasma generates a theoretical temperature of more than 15 000 °C through which the gas is passed (thus, lowering of the temperature) into the shaft. The fuel for the plasma is composed of electricity and air for combustion (oxidation). After the second reactor, chlorine, nitrogen, and all organic compounds are decomposed.

The raw gas after the plasma reactor is cooled and washed. The fly ash is collected and may be sent for recovery of some metals since they are separated in a reduced state. Apart from the wash water, a “clean” gas and hot water are obtained. Available data does not provide information to what extent flue gas treatment is required after combustion.

The molten slag is tapped from the bottom of the first reactor, and it is claimed to be non-leachable and easily disposable.

TPS Termiska Processer AB (TPS)

TPS is a privately-owned research, development and design company working in the field of energy technology. The company offers products and services, and performs research and development on gasification and combustion. The research is based mainly on laboratory experiments and on computerised flow simulation. Commercial exploitation of the new techniques developed by the company normally progress through large-scale demonstration plants to commercial operating plants. This type of exploitation has been achieved through technology licensing and joint venture activities. Research and development projects of TPS are often funded by STEM, the EU and private companies.

TPS was, or is, the designated technology supplier for the Grève-in-Chianti project in Italy, the Brazilian BIG-GT project and the ARBRE project, all of which were described earlier. TPS is also a partner in the Framework 6 CHRISGAS project.

TPS’s R&D work on biomass gasification began in the late 1970s. During the early 1980s, the work concentrated on the development of the MINO process for gasification of wood and peat to synthesis gas. This oxygen-blown process featured by high temperature filter and a catalytic gas cleaning device had a 2.5 MW output and was operated at up to 2.8 MPa.

During the latter part of the 1980s, research and pilot plant test work concentrated on the air-blown atmospheric-pressure CFB gasification process and its application to the thermal processing of biomass and waste fuels, featuring a patented gas cleaning step. TPS has a 2 MW atmospheric-pressure gasification pilot plant (fig. 3.13) on its premises.

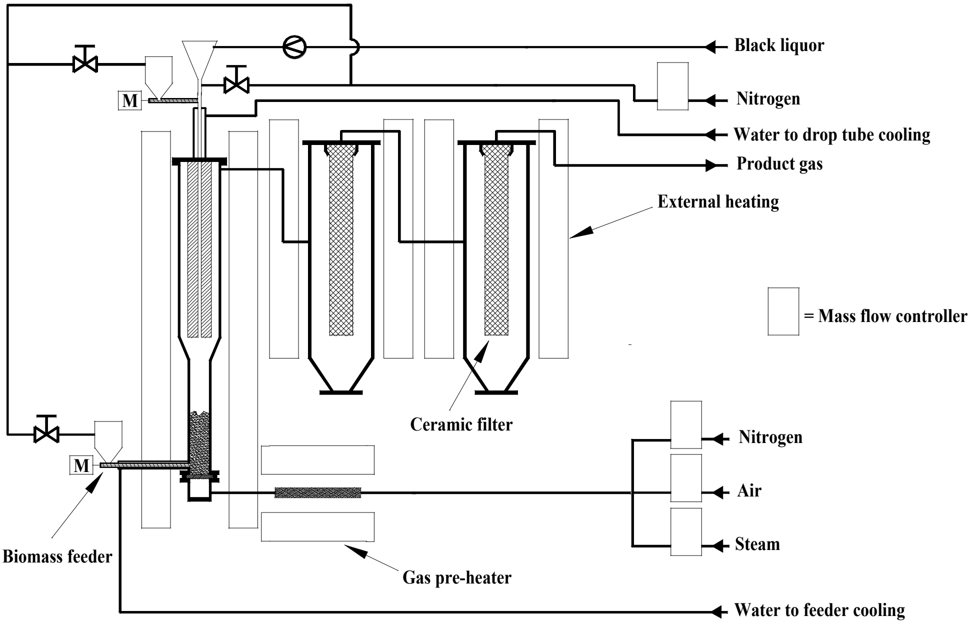

Fig. 3.13. Isothermal fluidised bed reactor

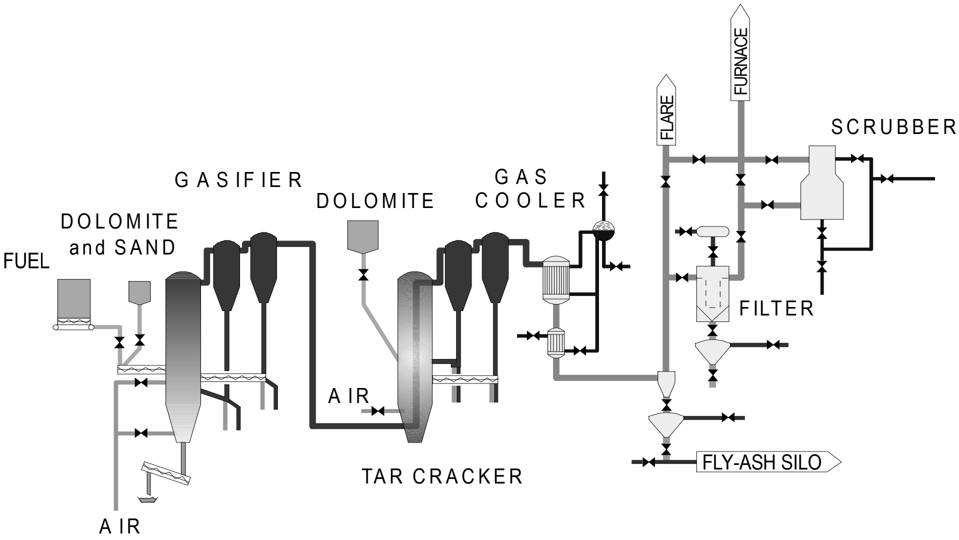

Fig. 3.14. TPS's ACFBG 2 MW pilot plant

This plant includes a CFB gasifier, CFB tar cracker, filter, wet scrubber and diesel engine. Over the last fifteen years, many hours of test work in this pilot plant using biomass and RDF as feedstock have been completed.

Only some data is revealed from the process. The power consumption for the plasma is reported as 200–400 kWh/tonne of feed – depending on the heating value of the feed. These figures imply the energy efficiency of roughly 65–80%.

Lund University (LTH)

Gasification research started at the Department of Chemical Engineering II, LTH in 1975 with work focused on oil shale gasification. The research group worked in close co-operation with Swedish mineral industries, and apart from TGA experiments, the majority of the work was directed towards development, construction, and operation of a laboratory-scale fluidised bed gasifier.

In 1978, pyrolysis and gasification experiments started, using biomass and other domestic fuels as feedstock. In these experiments, the gasification and pyrolysis kinetics of straw, sawdust, bark, peat, and lignite were investigated.

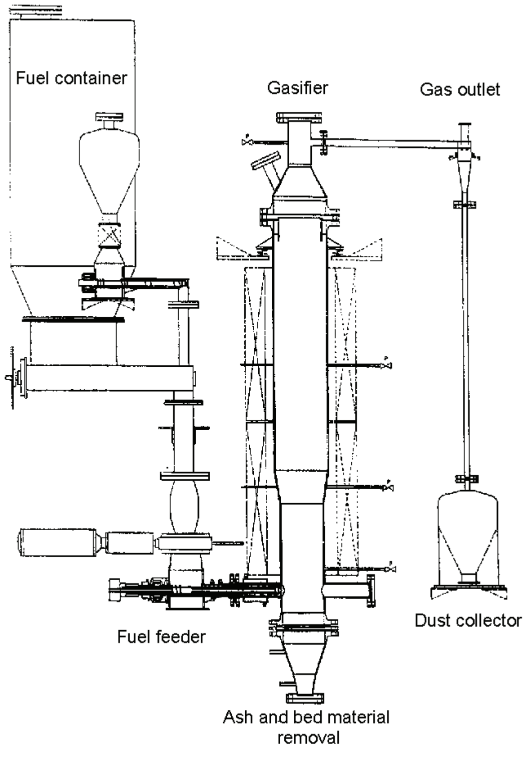

Fig. 3.15. The 20 kWt air-blown bubbling fluidised bed gasifier at TPS

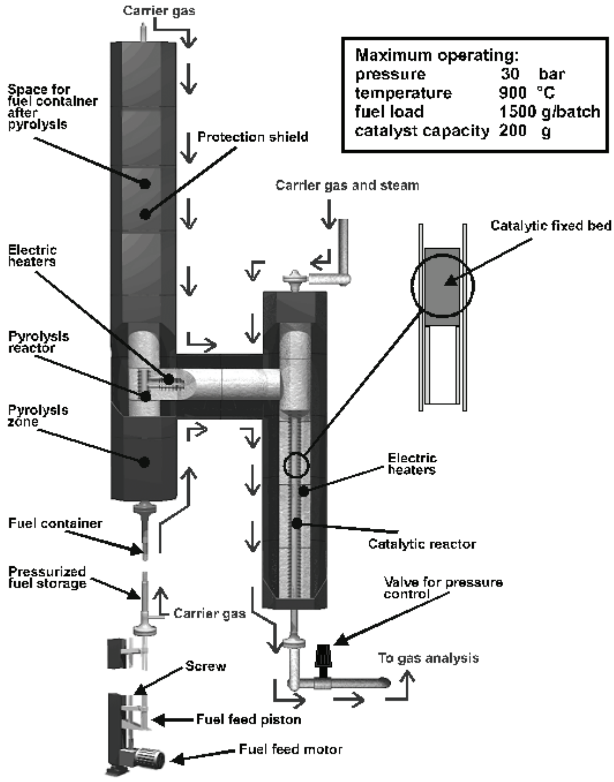

Fig. 3.16. 10 kW$_t$ nominal fixed bed gasifier/pyrolyser reactor

In 1981, a high-pressure TGA was built in which characterisation studies on peat and biomass were carried out. Gasification studies using a conventional fluidised bed gasifier were also performed. These activities were followed in 1985 by biomass thermochemical conversion studies in a specially-designed high temperature entrained phase reactor. In 1991, a government-supported evaluation of Swedish gasification research recommended expansion of pressurised biomass gasification research at the Department of Chemical Engineering II, and, as a result, a biomass PICFB (Pressurised Internal Circulating Fluidised Bed) gasifier test rig was installed at the Chemical Center at LTH. The installation work was essentially presented by the workshop at the Department and by PhD students involved in the project. This made it possible to keep investment in the installation low, the total investment cost for the equipment being estimated at less than SEK 6 million. Financial support for the first phase of the project was made available by NUTEK (now STEM), SEU/Elforsk and Sydkraft. The test rig was used for R&D on an assignment basis as well as in postgraduate research education. In addition, the test rig programme was supported by a variety of bench-scale test equipment for solid, liquid, and gas phase investigations.

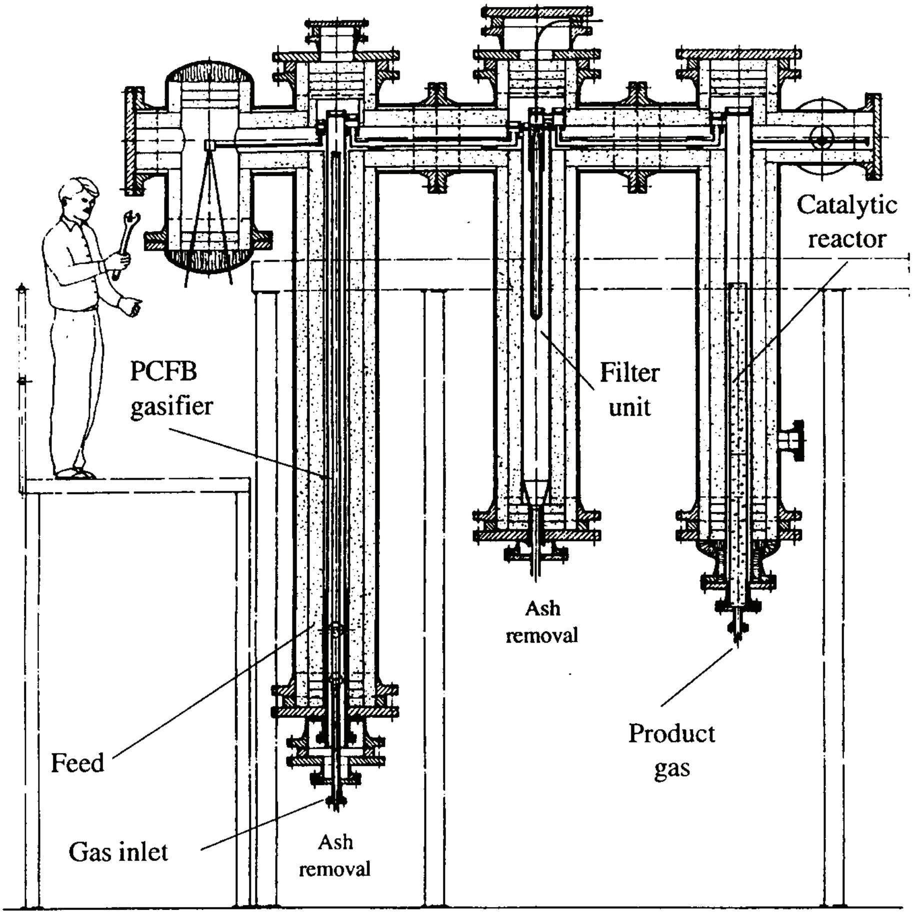

Fig. 3.17. The biofuel test ring at LTH

The biofuel PICFB gasifier test rig consisted of four main parts (fig. 3.17): feeder, PICFB, hot gas filter, reactor for the catalytic/thermal treatment of dust-free gas.

Operating parameters that gave a stable circulation of the bed material during the gasification mode were very difficult to achieve. After a comprehensive investigation involving more than 500 hours of test runs, the decision was made to abandon the internal circulating bed concept and to focus on bubbling bed operation.

From the mid 1990s onwards, the project group was involved in several EC-sponsored R&D projects where the PFB test rig played an important role in the experimental investigations. However, by the end of 2000 all the gasification activities at LTH had been terminated.

3.4. Austria

For the last years the part of bioenergy at the total energy production was about 11%. Austria has a strong policy on promotion and implementation of renewable energy. Austria has obligated a reduction of CO_2 emissions of 13% until 2010 [3]. Biomass has to play an important role for this reduction. The Ministry of Economic Affairs has defined to increase the production of electric power from renewables (hydro power not included) to 4% (at present 2.9%) until 2008.

Projects

Graz University of Technology – Institute of Thermal Engineering

- Evaluation and optimisation of a fixed bed gasifier, gas cleaning system and gas engine
- Scientific Partner in Austrian Bioenergy Centre
- Health, Safety and environmental issues for gasification systems

Graz University of Technology – Institute for Apparatus Design, Particle and Combustion Technology

- Fundamental research on biomass particles under gasification conditions
- Gasification and co-combustion in pulverised coal power stations

Joanneum Research Graz – Department of Energy Research

- Study on waste wood gasification

Vienna University of Technology, Department of Chemical Engineering

- Scientific Partner in RENET Austria (Network of Competence for Energy from Biomass)
- EC-Project “Clean Energy from Biomass” ENK5-CT2000-00314
- EC-Project “A New Approach for the Production of a Hydrogen-Rich Gas from Biomass – An Absorption Enhanced Reforming Process” NNE5-2001-00139
- EC-Project “Renewable Fuels for Advanced Power Trains” (RENEW)
- Scientific Partner in Austrian Bioenergy Centre

Table 3.9. Implementations of gasification in Austria

Location	Type, Capacity	Biomass feed	Subsidy	Status
Guessing	FICFB, 8 MW_t	wood chips	EC, 1a area	in operation
Civitas Nova	Fixed bed, 2 MW_t	wood chips	EC, 5b area	in operation
Gruebl	Fixed bed downdraft, 5–100 kW_e	wood chips	Local Government	2 gasifier in operation

CFB – Circulating fluidised bed, FICFB – Fast internal circulating fluidised bed.

GUESSING

In Guessing a Biomass CHP with the concept of the FICFB gasification system was realised. The basic idea of the FICFB concept is to divide the fluidised bed into two zones, a gasification zone and a combustion zone. Between these two zones a circulation loop of bed material is created but the gases should remain separated. The circulating bed material acts as a heat carrier from the combustion to the gasification zone. The fuel is fed into the gasification zone and gasified with steam. The gas produced in this zone is therefore nearly free of nitrogen. The bed material, together with some charcoal, circulates to the combustion zone. This zone is fluidised with air and the charcoal is burned. The exothermic reaction in the combustion zone provides the energy for the endothermic gasification with steam. With this concept it is possible to get a high-grade product gas without the use of pure oxygen.

The construction of the demonstration plant started in July 2000 and it started operation in November 2001. After first tests of the gasifier, the gas engine was started in April 2002. The total operation hours of the gasifier including the gas cleaning line were 9700 hours and of the gas engine 7100 hours till the end of March 2004. With this demonstration plant the scale up of the FICFB gasification process was realised and now the R&D on the gasifier and all ancillary units is going on, so that the turnkey contractor Repotec can bring an economical and commercially viable biomass driven power station to the market. The developmental aim is a current-led heat power combination with high electrical efficiency for larger capacity applications.

CIVITAS NOVA

In Wr. Neustadt/Civitas Nova a small Biomass CHP demonstration unit has been built. This system is a demonstration plant for marketable, economical and modularised installation systems for small capacity applications such as local heat supply systems or the woodworking trade and industry. As a gasification system, a co-current gasifier was realised. Electricity is produced using a gas engine. The biomass input is 2 MW and the electric output is 0.6 MW. As a gas treatment system a scrubber with a wet electrostatic precipitator is installed. The plant went into operation in February 2003. The first electricity was produced March 1st. At the moment the optimisation work is going on.

GRUEBL

The company Gruebl Automationtechnic produces woodgasifiers for production of heat and electric power in the size from 5–100 kW_e [10]. This system consists of the following components:

- a sluice system to feed wood chips into the gasifier,
- a fixed bed downdraft gasifier is used to produce gas from wood,

- the product gas cleaning system consists of a cyclone, a heat exchanger and a scrubber.

At the moment 2 gasifiers of size from 5 to 50 kW_e are in operation.

The main market for this type of gasifier will be farmers and small scale industry.

3.5. Belgium

The Federal Belgian Government adopted the 1994 master plan for Greenhouse gases emissions reduction. This national plan aims at reinforcing actions for the Ratiola Use of Energy and the valorisation of Renewable Energy Sources. This includes mainly the promotion of cogeneration and the support of emerging technologies and Renewable Energy Technologies. By 2010 renewable energy should contribute to about 5% of the total energy production. Priority will be given to biomass, small hydroelectric plants and solar thermal technology.

Projects

1° The SRC GAZEL project: Development of downdraft gasifier dual fuel system with a nominal capacity of 150 kW_e. The plant has been running fully automatically on Short Rotation Coppice since September 2000, feeding the produced electricity in the local low voltage grid. A long duration test has been completed so far.

2° The REGAL project: this project aims at developing a commercial 300 kW_e + 600 kW_t CHP plant based on gasification. The test period is coming to its end and the plant will run from November 2002, feeding the produced heat in the local university heat network. It is a technical improvement of the GAZEL plant.

3° The Waste Wood COGEN project: in Belgium waste wood is a problem Environmentally sound technologies to valorise this energy potential do not exist. Small scale gasification is an attractive way to convert wood into heat electricity because most pollutants are destroyed in the gasifier or kept in the high efficiency filtration system. The project aims at measuring different types of waste wood pollutants in exhaust gases, including dioxins and to compare it with European legislation. The gas cleaning system could be improved to treat some of special pollutants and to satisfy environmental legislation.

4° The MINI-COGENBOIS project: In Belgium an important part of the wood resource is a local resource. It will be interesting to valorise it locally to avoid transportation. This project aims at developing a standardized small scale CHP plant (20–50 kW_e + 40–100 kW_t) based on a downdraft gasifier coupled with an internal combustion engine.

5° The Biopower Ruien project of ELECTRABEL: Co-firing of pulverized wood in the existing coal plant. The gasifier capacity is about 8.5 t/h and converts

40 000 tons of non-contaminated wood yearly (first phase, 14 MW_e). The project is based on a CFB gasifier. The second phase started production of power (17 MW_e, 50 MW_t) with an electrical efficiency of 34%, converting more than 100 000 tons of biomass (contaminated and non-contaminated wood).

Implementation

1° THE SRC-GAZEL PROJECT: SHORT ROTATION COPPICE GASIFICATION FOR DECENTRALISED PRODUCTION OF PEAK ELECTRICITY.

This project aimed at studying technical, economic and environmental feasibility of electricity production based on cultivated wood at a farm level. Currently a full automatic 150 kW_e gasification plant is working in a farm (20 km from Brussels) and delivers its electricity to the grid. SRC-GAZEL project, funded by the Walloon government together with Electrabel and involving four research centres, aims at developing and characterising a complete route from wood cultivation to electricity production by wood gasification, and delivering this electricity to the grid.

What is specific to this route:

- Localisation in a rural place near crops, and small power (100–500 kW_e) in order to reduce transportation distance,
- Peak electricity production for high electricity selling price,
- Automatic plant control and management for low maintenance and high reliability.

2° ECONOLER has been built in the neighbourhood of Liege – a 150 kW_e biomass gasification plant, based on a downdraft gasifier coupled with a V8 gas engine from Deutz. The system is constructed by AHT Germany and will accept only clean wood. There are some technical problems now and the plant is not in operation. Unfortunately the plant could not operate due to time delay in the commissioning period and the outbreak of fire in the wood storage facility.

These projects are co-funded by the Walloon government and by Electrabel and realized by the Groupe Energie Biomasse from Université catholique de Louvain. All these projects are R&D projects. The total funding of these project is about 3 million Euros.

3.6. Denmark

The Danish energy plan Energy 21 was introduced in 1996 in order to ensure a strong Danish energy supply system, with the emphasis on short-term targets, and preparation of longer-term sustainable development.

The important objective is to reduce the CO_2 emission by 20% by the end of 2005 compared to the 1988 level, and 50% before 2030. The energy plan states that Demark has to be a driving force in international development of renewable energy with ambitious environmental goals, and to support the European opening of the energy market, with strong priorities on the environment. Further the Energy 21 confirms the need for dynamic, revised energy plans.

The current Danish energy policy states that Denmark will use the Kyoto mechanisms and buy CO_2 reductions where they are most profitable.

Some years ago the utility companies owned both the grid and the power plant. Then that was split up in two utility companies ELSAM and Energy E2 and at the end of year 2004 the two grid companies Eltra and Elkraft System by law will become one company. The utility companies are now allowed to make profit and the Grid Company will be a part of the Civil Service with no profit.

New laws for CO_2 quota allocation for all Energy production with fuel input higher than 20 MJ/s regulate the production from January 2005 to full fill the Kyoto protocol. Every utility company, industry and private Energy production have to make a forward planning before the end of the year to fulfil this requirement.

Implementation

Harboøre CHP plant

In 2000 a complete biomass gasification process system fitted with two gas-engines of total 1.4 MW_e was set in operation at Harboøre district heating plant. This was the final step in a development process, which started in 1988.

Based on a traditional German updraft moving bed gasifier Volund in 1988–1992 experimented with a pilot unit for straw gasification. Next step was the construction of a wood-chip fired version of this gasifier, which since 1993 has been supplying gas to the boiler at Harboøre district heating plant, and since 1996 the gasification plant has produced all district heating for Harboøre, with minimal operating staff. The final conversion to a CHP plant was completed in the summer of 2000. The gasifier has been operating for 74 000 hours (8100 hours/year since 1996).

Since July 2000 the engines have been operating for 9100 hours and 6400 hours, the CHP power to the grid has been 7700 MWh and the CHP district heating 65 000 MWh in total. Since December 2003 the engines has been fully available. The operational data for the period until today (July 2004) are, woodchip fuel with a moisture content varying between 39 and 50%, 3691 MWh of power to the grid, corresponding to power efficiency (woodchips to power) of 27.2%.

Ansager Stirling

In 1999 the Technological University of Denmark received national funding for the development of a 2nd generation Stirling unit. In connection to this project Volund received national funding for implementation of a combined Stirling/gasifier unit. The project in Ansager includes an updraft Volund gasifier, fired with wood chips up to 50% moisture. The gas is led directly to the burner on top of the Stirling engine combustion chamber without any gas cleaning.

The plant has been operating for approximately 400 hours, and several improvements have been made. An electric power output of up to 37 kW has been measured, which is well above the predicted 35 kW. The results of a one-hour test showed that a net electric efficiency of 16.7% (woodchips to power) was obtained and the total energy conversion efficiency was 88%. The project is being reconstruced in 2004 and results are expected at the end of the year. The Danish company FLADDER International will operate the plant in the field test, which will soon be initiated [11].

Løgstør CHP plant

The community of Løgstør produce heat from straw fired boiler, and have together with KN Industries have received national funding for the two first stages of the project including building of a first generation small scale demonstration plant, and a 2000 h test run of the gasifier located at the supplier. The straw fired gasifier, using CO_2 as a gasification agent, has been developed by KN Industries. Before the final stage, of implementation at Løgstør is funded and initiated, a successful outcome of the test run is required.

Kibæk CHP plant

In 1996 the community of Kibæk received national funding for implementation of a steam based CHP plant. In 1998 a review of the plant design and implementation showed an advantage in choosing a 2 generation of the Volund Harboøre gasifier, fired with wood chips (50% moisture) instead of the steam cycle. The gasifier is designed to have an installed capacity of 3 MW_e (31%) and 6 MJ/sheat. The total efficiency is expected to reach 92%. Contractual negotiations with two different companies are still ongoing.

Skive CHP plant

I/S Skive Fjernvarme (District heating company in Skive town) has received European, US and national funding for a project aiming at the installation of a new biomass fired gasification plant producing gas for 3 biofuel modified gas engines, built in connection with an existing biomass boiler plant. The plant is a fluidized bed gasification plant (Carbona) utilizing palletised bio fuels. The plant will have an installed capacity of around 20 MW base load and 28 MW extended load.

The local authority and the City Council of Skive has both approved the project and adopted the main part of the necessary permits, allowing the project to move into the construction phase.

Engineering work on the plant building and the district heating system is nearly completed.

Gjøl

Gjøl Private Kraftvarmeværk (District heating company in Gjøl) has received National and European funding for the establishment of a wood chip fired gasification unit, in order to be able to produce gasification gas for two existing natural gas fired Jänbacher engines, which will be modified to accommodate the gasification gas. The plant delivers heat for 300 housings, the annual heat sale is 5500 MWh and the electrical sale is 5900 MWh. TK Energi A/S will deliver the gasifier, based on an open core gasifier and a patented wood chip dryer and dry gas cleaning technology. All necessary approvals have been obtained from the local authorities for the project to move it into the construction phase. The construction of the building and the installation of the grab crane system and the biomass boiler will commence shortly. The consortium consists of Gjøl, TK Energi, FORCE Technology and European partners.

Græsted

Græsted Fjernvarme (Græsted district heating) is hosting the BioSynergi demonstration CHP pilot plant. The activities are performed in the ongoing project: Optimizing and automatic operation of an Open Core gasifier pilot plant for combined heat and power with wood chips as fuel, funded by the Danish Energy Authority.

The aim is to demonstrate and optimize a staged Open Core gasifier fuelled with forest wood chips (45–50% moisture on wet basis), as a part of a CHP plant.

The electrical output from the pilot plant is designed to 90 kW_e and the thermal heat output to 200 kJ/s. The plant includes all components from wood chip storage and drying to output of energy in the manner of electricity for the electric distribution network and heat for the delivery to the private district heating plant in the town of Græsted.

The completion of the plant and supply lines to the heat and electricity networks occurred in 2003. The first half of 2004 was dedicated to test the individual components and minor improvements of the plant design, leading to the ongoing long-term test period. Unmanned operation will be implemented as soon the safety procedures are tested with a satisfying result. The long-term test period is settled to 3000 operation hours. The future goal is to up-scale the CHP plant to 250–1000 kW_e output.

Weiss A/S

A 200 kW_e pilot plant of the two-stage gasification process is being established at the factory of Weiss A/S. In the two-stage gasification process, the pyrolysis and the gasification processes are separated into two different zones. Between the pyrolysis and the gasification zones, the volatiles from the pyrolysis are partially oxidised. Hereby, most of tar is decomposed into gas. To enable high energy efficiency, the thermal energy in the gasification gas and the exhaust gas is being used for drying, air preheating and for pyrolysis.

The two stages of the gasification process has successfully demonstrated that the process offers:

- Low tar content in gas (<5 mg/Nm^3),
- Stable unmanned operation,
- High coldgas efficiency (>95%),
- Low environmental impact (high carbon conversion).

The process verification and documentation has been performed in a small scale, and in order to manufacture economically attractive plants the process is now being upscaled. The two-stage gasification process is modified, so the drying is separated from the pyrolysis unit. The drying agent is steam and the produced steam from the dryer is led to the pyrolysis-gasification reactor, and hereby soot production is reduced and char reactivity is increased.

3.7. Finland

Finland is first among the states of the industrialised world which use biomass:

- 19% of primary energy production based on wood fuels in 1998,
- 10% of power production based on wood fuels in 1998 [12].

Projects

R&D Projects at VTT:

- CFB gasification of waste-derived fuels,
- Fixed-bed gasification of wood residues and waste-derived fuels,
- Development of selective catalytic oxidation (SCO) technology,
- Scrubbing of gasification gas,
- Participation in the EU Tar Protocol project,
- Synthesis gas production for liquid biofuels.

Implementations

Lahti Kymijärvi Plant

In 1997 and 1998, the Lahden Lämpövoima Oy, installed a 60 MW$_t$ capacity atmospheric pressure Foster Wheeler CFB biomass gasifier, at a cost of approximately US$ 15 million at its 200 MW$_e$ fossil fuel fired power station. The gasifier is a single gasifier vessel with a cyclone and air preheater for heating the gasification air to approximately 400 °C. The LCV-gas is cooled from approx. 830–850 °C to 700 °C before it is transported in a pipeline to the boiler. The raw gas has no adverse effect on the performance of the boiler. Emissions are reduced and the heating surfaces in the boiler stay relatively clean. The reported gas composition (in vol.%) is given below:

CO_2	12.9	N_2	40.2
CO	4.6	H_2O	33.0
H_2	5.9	C_xH_y	3.4

The heating value of the LCV gas is approximately 2.0–2.5 MJ/Nm^3. The NO_x emissions were reduced by 5% (permitted level is 230 mg/MJ for both NO_x and SO_2) and the dust emission were reduced by half because of the increased conductivity of dust. However, HCl emissions increased by a small quantity of 5 mg/Nm^3. The present breakdown of fuels in the boiler is approximately: 11% LCV fuel from the gasifier, 69% Coal, 15% Natural gas to the boiler, and 5% Natural gas to the gas turbine. The plant supplies 200 MW$_e$ power to the national grid (110 kV line round the town) and 250 MW$_t$ heat to the town (100 000 inhabitants) and surrounding houses (main pipe 700 mm). The district heat system was constructed in 1958.

The 200 MW$_e$ power plant was initially built in 1976 for using fuel oil. In 1982 the plant was converted to coal at a cost of approximately FIM 180 million (US$ 34 million) and the pay-back was only within 3 years. In 1986 the burners in the boiler were converted to natural gas, and a natural gas turbine cycle was added to the power station. The biomass gasification plant was installed primarily to use locally available fuels and waste materials including plastics. The annual average total efficiency is ~80%, the fuel to power efficiency with the gas turbine in operation is 35%. The gas turbine has increased the efficiency by 4% points.

BIONEER Process

The BIONEER gasifier is an updraft moving bed gasifier, producing tarry LCV fuel gas. The gasifier consists of a refractory lined vessel with a rotating cone-shaped grate. Biomass fuel is fed from the top, from where it flows downwards through drying, pyrolysis, gasification and combustion zones. The residual ash is discharged from the bottom by the rotating grate. The temperature of the combustion zone is regulated by humidifying gasification air. Air and steam are fed as the gasification media through the grate. Since updraft gasification produces raw gas with a significant amount of tar, the gas cannot be either transported for long distances or directly used in IC engines. In the existing BIONEER plants the gas is burnt in a close coupled boiler to generate steam and hot-water for district heating. In the mid 80's, VTT and BIONEER conducted extensive tests with a variety of feed stocks (e.g. wood chips, forest wastes, peat, straw, RDF pellets, coal and RDF mixed with wood chips) in a 1.5 MW$_t$ pilot plant located at BIONEER's Hämeenlina works. A typical gas composition with 41% moisture content wood chips consists of 30% CO, 11% H_2, 3% CH_4, 7% CO_2, and 49% N_2, with a HHV of 6.2 MJ/Nm^3. The tar content of dry product gas is estimated to be in the range of 50 to 100 g/Nm^3. Between 1985 and 1986, when fuel oil prices were high, eight commercial BIONEER plants, with capacities ranging from 4 to 5 MW$_t$, were commissioned, five in Finland and three in

Sweden. Four plants are operated with wood or wood and peat mixtures while the rest are operated with peat only. Most of the gasifiers are in operation at small district heating plants to provide circulating hot water. The BIONEER plants are completely automated and operated with minimal personnel costs. A. Ahlstrom corporation bought the BIONEER company originally owned by YIT Corporation. After Foster Wheeler acquired Ahlstrom, in 1996 a 6.4 MW_t plant was installed at Ilomantsi, in eastern Finland. The estimated investment cost for district heating applications is about 350 $kECU/MW_t$, operating cost is about 17 ECU/MWh, and heat generation cost is about 20 ECU/kWh.

Wisa Forest Pyroflow Gasifier

Description: In 1981, A. Ahlstrom developed the first 3 MW_t capacity pilot CFB gasifier from its successful CFB pyroflow combustion technology at the Hans Ahlstrom Laboratory at Karhula. The first commercial Ahlstrom Pyroflow CFB gasifier was commissioned in 1983 at the present Wisa Forest Pulp and Paper Mill in Pietarsaari, Finland. The fuel for the 35 MW_t (about 150 TPD of biomass) gasifier is primarily bark and saw dust sized up to 5 cm and dried at 150 °C to about 15% moisture content. The biomass is fed from the side into the circulating sand of the air-blown CFB gasifier maintained at about 900 °C. The hot fuel gas at 700 °C is fed directly to the lime kiln. The objective of replacing 85% of the fuel oil for the lime kiln was achieved within a few months after the start up. Between 1985 and 1986, three more gasifiers, two in Sweden (25 MW_t at Norrsundet Bruks, AB, Norrsundet and 27 MW_t at ASSI, Karlsborg Bruk, Karlsborg) and one in Portugal (15 MW_t at Portucel, Rodao Mill), were built and commissioned for firing lime kilns.

Varkaus gasification plant

Corenso United Oy Ltd. has built a gasification plant for energy production and aluminium recovery at its coreboard mill in Varkaus. The plant supplied by Foster Wheeler enables the complete exploitation of used packages containing wood fibre, plastic, and aluminium. It is the first plant in the world able to recycle aluminium in used liquid packaging to create a raw material for foil for its original purpose, while simultaneously exploiting the plastic contained in the packages to produce energy.

In Corenso's new gasification plant, the fibre material in multi-layer packages is recycled in coreboard, the aluminium is recycled in raw material for foil. The remaining plastic is gasified to create energy. The metal and packaging bands in the loads of collected raw material are sent to metal industry for recycling. Thus, everything is recovered.

The cost of the new plant being built was around EUR 17 million. Finland's Ministry of Trade and Industry has allocated about EUR 3 million to the project. The investment includes the gasifier, an aluminium recovery unit and new boiler designed specially for gasification gas.

The gasification plant generates about 40 MW of heat, with an estimated annual total energy production in the region of 165 GWh. An additional benefit will be the resulting improvement in air quality. The plant was taken into commercial operation in autumn 2001 and has operated with high availability since then (monthly gasifier availabilities >90–95%).

ENTIMOS gasifier

Entimos Oy (established in 1997) has constructed a new type of gasifier and a CHP plant in Tervola, which is a community of ca. 2000 inhabitants in Lappland. The gasifier combines features from both updraft and downdraft gasifiers and is based on innovations partly originating from the times of the WWII. The special feature of this gasifier is two product gas lines: Gas B that is directly combusted, and clean gas A which is utilised in an engine.

The main features of the process are:

- combined updraft and downdraft gasification,
- innovative feeding, grate and ash removal systems,
- adjustable in large range: 20–100% of nominal capacity.

The gasifier and the district heating system have been in operation producing district heat to the Tervola centre, while the gas cleaning and engine use is under commissioning phase in autumn 2002. The gasifier has fuel capacity of 2 MW and it is connected to a boiler and an Jenbacher engine. The plant will generate 1.1 MW of heat and power about 450 kW which corresponds with about 90% of the district heat and 10% of the power capacity required by the Tervola community. Local feedstocks will be used, such as various residues from sawmills and forest waste wood.

Puhdas Energia Oy

Puhdas Energia Oy located in Tampere Finland is developing a small scale CHP process based on downdraft gasification. The objective of this project is to develop a commercial unit available in the capacity range of 100–3000 kWt for farms, greenhouses and communal CHP stations. The project has focused on the R&D of the gasifier and automation of the process.

The main features of the process are:

- new design of the gasifier internals,
- stable operation with pellets and other good quality fuels,
- simple construction and low investment costs.

Ekogastek waste gasification process

Ekogastek Oy constructed a full size test plant (4 MW) for waste gasification in town Lappeenranta in East Finland. It is based on updraft gasification equipped with innovations of Russian origin. The plant was commissioned 1998 and it has been tested with various waste derived feedstocks. The special feature of the gasifier is the operation based on the circulation of ceramic balls that are fed to the gasifier with the fuel and removed from the ash.

NOVEL gasifier

VTT Energy and Condens Oy have developed a new type of fixed-bed gasifier, which is based on forced fuel flow and consequently allows the use of low-bulk-density (of the order of 150–200 kg/m^3) fibrous biomass residues. Presently a pilot-scale process is installed in the test hall of VTT with a nominal design capacity of 500 kW$_t$. This plant is of the same quality as commercial gasifiers and can be directly scaled up to the first demonstration plant. Condens Oy is offering the Novel-technology both for heat alone and combined power and heat applications. The gas cleaning train based on VTT's catalytic gas cleaning know how followed by special wet scrubbing has been demonstrated in the pilot plant and turned out efficient enough to allow the use of gas in turbo-charged gas engines.

The main features of the process are:

- fuel feeding is not based on natural gravity alone,
- suitable for various biomass residues and waste-derived-fuels,
- high carbon conversion and low tar content,
- can be scaled up to 8 MW,
- no problems with leaking feeding systems or blocking gas lines,
- demonstrated at pilot scale with
  - forest wood residue chips,
  - sawdust and wood shavings,
  - crushed bark,
  - demolition wood,
  - residues from plywood industry.

3.8. France

Centralised and powerful structures such as EDF, the French Electricity Board or the CEA, the Nuclear Power Committee, and their influence on the policy making process are the main characteristic of the French energy policy. The priority which has been given to the nuclear industry, and then its success, has been detrimental for the development of the entire renewable energy sector and particularly for the electricity production as well as for the auto-production through cogeneration projects.

Since 1993, the signature of an agreement between EDF and the ADEME to develop the Demand Side Management for the electricity sector in rural or remote areas has slightly changed the renewable energy scene. Pilot programmes are now launched together with local electrical grid authorities to promote electricity savings and the use of renewable energies for remote places not connected to the national grid.

But ministerial order fixing purchase price for electricity from biomass in France was published at the beginning of May 2002. The price is 4.9 ceuros/kWh$_e$ (comparing to 15.25 ceuros/kWh$_e$ for solar and 8.38 for wind energy) with a premium according to efficiency (1.2 ceuros/kWh$_e$ for a global efficiency higher than 70%). This price is clearly insufficient and does not encourage project elaboration on electricity production from biomass until 2010.

Projects

Two R&D programmes have just been completed on gasification, both being supported partly by the European Union with Cirad as co-ordinator.

Clean biomass staged gasifier based on a new tar cracking and ash slagging techniques for efficient CHP generation (Ref. JOR3-CT98-0220)

The developed approach consists in:

- Introducing a new device called Total Char Combustion and Tar Cracking Chamber (TCC)2 between the pyrolysis unit and the char reduction chamber in a stage divided gasifier. With this design, the char conversion takes place in 2 stages. The first stage is the char reduction Chamber (CRC) which main purpose is to convert as much as possible carbon of the char supplied directly from the pyrolysis unit into gas by means of reduction reactions. The second stage takes place in the (TCC)2 whose purpose, with respect to the char, is to perform a complete conversion of the remaining carbon from the CRC drain off and where pyrolysis gases are thermally cracked, and residual ashes vitrified and eliminated as slag.
- Designing and implementing a new vibrated fluidisation pyrolysis unit able to achieve an appropriate and constant quality of char with minimum preparation of biofuel with a good phase separation.
- Offering the opportunity to orientate the process for gas and solid reactions according to plant requirements and market conditions.

For all industrial partners the scopes were:

- to eliminate the present and costly tar cleaning set up,
- to increase the process efficiency with a carbon content in ashes close to zero,
- to obtain a cleaner gasification process,
- to eliminate operational problems arising from a low melting point of biomass ashes, owing to the vitrification process.

3.9. Germany

National aims for minimizing green-house gases and soil contaminants, for lessening the overwhelming dependence on oil and gas resources in conflictive international regions, have been elaborated by the Bundestag (Federal Parliament) and the Federal Government. This process was facilitated by the European Union (f.i. “White

Paper Energy for the Future: Renewable Sources of Energy", "Green Paper Towards a European strategy for the security of energy supply" and relevant guidelines on renewable energy, biofuel etc.), the Kyoto and Johannesburg-Processes and activities of non-governmental organisations. The founding of the International Partnership for Hydrogen Economy and the European Hydrogen and Fuel Technology Platform stipulated gasification for hydrogen rich gas.

In the EU-Europe the total mineral oil based fuel demand should be substituted by bio or new fuels to 2% in 2005 and 5.75% in 2010. In Germany by 2005 carbondioxid-emissions should be decreased by 25% in comparison to 1990, in 2010 the power supply from renewable sources should be doubled to 12%. Only recently the Federal Government has published the Environmental Report setting the target for the final energy supply from renewables to 50% by 2050.

Projects

Major trends in biomass gasification have changed substantially:

- This modified situation caused an enormous upswing of gasification to produce syngas. Even first projects to prepare the use of gasification gas in fuel cells started.
- The first ever strategic partnerships between global players (automobile industry, mineral oil companies) and innovative small and medium sized enterprises (SME) were formed. Additionally, to the first strategic network formed by research institutes, enterprises, specialized on gasification, automobile industry for the development of biofuel and fuel cells, comprising CHORen Industries GmbH, Freiberg, DaimlerChrysler AG, Stuttgart, (methanol), UET Umwelt- und Energietechnik Freiberg GmbH and Volkswagen AG, Wolfsburg, (SunfuelTM), a second one formed by CUTEC – Clausthaler Umwelttechnik Institut GmbH, Bundesland Lower Saxony and Volkswagen AG was added.
- The technology of first choice is the entrained flow gasification.
- The interest rises in co-gasification of biomass and residues, especially sewage sludge and municipal solid waste, and the mono-gasification of waste.
- This ambiguous situation led to growing insecurity of public authorities and negligence of their necessary support.
- In relation to worldwide growing pressure to cleaner coal combustion processes with less or no CO_2-emissions, possibilities to integrate gasification technology into a combined process are being investigated. Only recently the engineers of the former VER GmbH have presented a promising path.

The current state-of-the-art is characterised as follows:

- The overall situation did not change. There are still at least 35 test-, pilot- and demonstration and the very first commercial plants for combined heat and power generation or production of methanol or synthetic gas, as well as refuse disposal and recycling, realized or in operation in Germany or with German technical participation abroad. They range from 10 kW to 100 MW installed thermal power. In this case, plants in scientific institutes are not counted.

- An extraordinary variety of technologies, performances, fuel, gasification and application aims prevails.
- As far as mini, small and medium scale plants are concerned, up to now in no case unlimited marketability could be achieved, but the first plants could accumulate several thousand operation hours.
- In almost all old and new processes where gasification was developed as a uniform continuous process but with certain clean separation of the four main partial phases the developers made promising progress.
- The majority of projects are either suffering from technological immaturity, insufficient investment due to deficiency of own capital resources and enforced discontinuous development.
- Innovative small and medium sized enterprises are still the main driving force, sometimes supported by research and scientific institutes.
- Efforts to concentrate technological development in a biomass gasification center failed, but to organize networking for accelerating R&TD as well as demonstration were successful.

3.10. Evaluation and conclusion

This chapter presents the results and status of the development of gasification systems in 10 countries that participate in the **IEA Bioenergy Thermal Gasification of Biomass** Task 33, and 16 countries within the **European Gasification Network**, **GasNet**. It shows considerable activity to develop and demonstrate biomass gasification for efficient and environmentally acceptable energy conversion applications [12].

The review of what has been achieved in the area of biomass gasification over the past 10 years shows that there is still R&D work needed on the gasification process and gas cleaning. Nevertheless several developments have resulted in successful pilot plants, and working demonstrations. However, only very few projects have achieved a commercial status, that is, where the technology has a competitive advantage on the market; in particular for heat applications.

Cofiring of fuel gas is on the competitive edge, as proven by several demonstrations, due to the fuel flexibility and the avoidance of emissions. Zeltweg and Amer have proven that for this type of application the operation of the gasifier is very dependent on the status of the power plant itself.

On a small scale, fixed bed gasifiers will have such advantages as high electric efficiency, and the possibility of using waste heat on-site. The highest reported efficiency is 36% and longest test run of 1000 hours. Harboore gasifiers have run for about 70 000 hours and the engine about 10 000 hours, i.e. this plant can be seen as a commercial unit. Most demonstrations, however, show practical problems with the system, or the effluents (ashes or wastewater).

Many think that the IGCC concept is the potential future star of all applications, and tests and verification will be needed to prepare it for this role. Recent developments show high technical and financial risks associated with large scale concepts. Co-firing in coal/oil or natural gas boiler with advance steam condition is also promising, since it almost reaches the same level of efficiency. For small scale application fixed bed can be attractive in CHP and a good efficiency can be obtained.

Most recent trend is syngas production for methanol, Fischer Tropsch diesel and/or hydrogen production.

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Chapter 4

Thermodynamics of low and high temperature biomass gasification

The biomass as a renewable energy sources can be used directly for heat generation or indirectly as a syngas producing by biomass gasification process. The different type of gasification processes has been developed, which produced different type of syngas composition with different tar concentration. By thermodynamic calculation and assumption the limiting concentration of main components in syngas obtained by low and high gasification temperature has been calculated. On basis of these results the plasma gasification process for high temperature biomass gasification has been suggested.

4.1. Introduction

At present time the re-discovered biomass gasification processes, which were intensively used 60–70 years ago, mainly for fuel production in the cars, are intensively studied.

The biomass gasification process is a thermal conversion of solid carbohydrate fuel $C_6H_{10}O_5$ at a relevant temperature and reducing atmosphere into a syngas with variable contents of CO, H_2, CO_2, $H_2O_{(g)}$, CH_4, tar, etc. and ash or charcoal as minor products.

The different types of biomass gasification processes, quite similar to coal gasification processes, has been developed. The main types of gasification reactors are:

- updraft gasifiers,
- downdraft gasifiers,
- fluid bed gasifiers,
- entrained beds gasifiers.

The schematic diagrams with different types of gasifiers are presented in fig. 4.1 [1], and the syngas compositions produced by different types of gasifiers are summarized in table 4.1 [2]. Table 4.1 shows that different types of gasifiers produce syngas with different composition and higher or lower tar concentration, which is the main limitation factor, as is documented in tab. 4.2, for different usage of syngas [3].

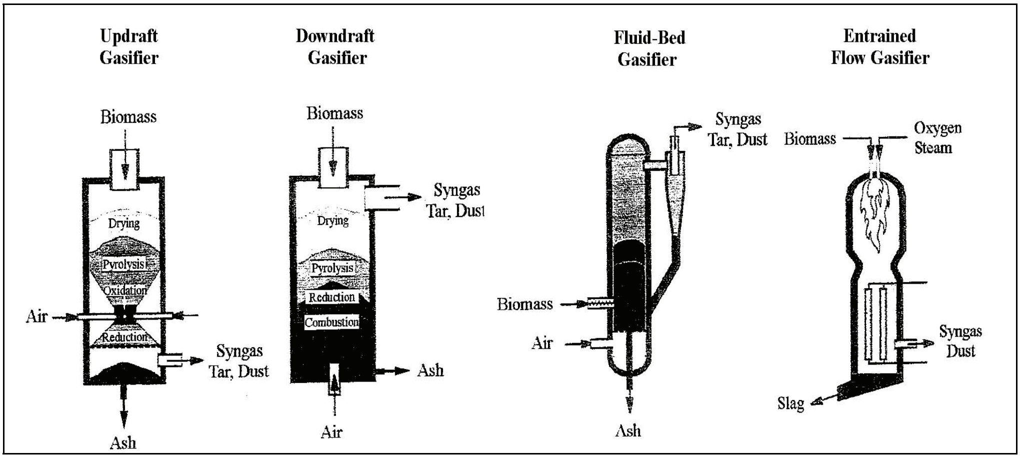


Fig. 4.1. Schematic diagrams of different types of gasifiers [1]

Table 4.1. The syngas compositions producing by different types of gasifiers [2]

	Unit	Updraft Gasifier	Downdraft Gasifier	Fluid-Bed Gasifier	Entrained Flow Gasifier
Reactor temperature	°C	700–900	700–1200	750–950	~1500
Syngas temperature	°C	75–150	850–1000	650–850	1100–1300
Syngas composition					
H_2	%	7.0	18	11.2	22.1
CO	%	7.4	23	20.2	21.8
CO_2	%	16.5	10	12	11.4
CH_4	%	2.5	2	5.8	0.1
N_2	%	63.6	45	44.6	44.7
Tar	$g \cdot Nm^{-3}$	50–150	0.1–2	1-50	–
Heating value	$MJ \cdot Nm^{-3}$	4.18	5.55	5.86	5.16

Zuberbühler at al. [4] shows that the heating value of syngas depends strongly on the gasification agent that can be air, oxygen or steam as it is documented in tab. 4.3.

Table 4.2. Permissible concentration of dust, tar, sulphur and alkali in syngas for different applications [4]

Application	Heating value (MJ·Nm^{3})	Syngas Composition			
		Dust	Tar	H_2S	Alkalis
		(mg·Nm^{-3})	(mg·Nm^{-3})	(mg·Nm^{-3})	(mg·Nm^{-3})
Combustion	>4	no limit			
Engine	>4	5–50	<100	<700	1–2
Gas Turbine	>4	<5	<5	<1	<0.2
Fuel Cell	>4	<0.1	<1	<0.1	<0.1
Methanol production	>4	<0.1	<1	<0.1	<0.25

Table 4.3. The compositions and heat value of syngas versus gasification agent [4]

Gasification agent	Syngas Composition (vol.%)					Heating value (MJ·N m^{-3})
	H_2	CO	CO_2	CH_4	N_2	
Air	15	20	15	2	48	4.85
Oxygen	40	40	20	–	–	9.36
Steam	40	25	25	8	2	10.33

4.2. Thermodynamics of wood combustion/gasification process

Wood consists of cellulose, hemi-cellulose and lignin. It is carbon based and is composed of a mixture of organic molecules which also contains water, small amounts of sulphur, nitrogen and some inorganic compounds, that remain as ash after the combustion is complete. The proximate analysis of different woods and wood pellets are summarized in table 4.4.

Table 4.4. The proximate analysis of oak wood, spruce wood and wood pellets

Wood	Moisture (wt.%)	Volatiles (wt.%, dry)	Fixed carbon (wt.%, dry)	Ash (wt.%, dry)
Oak	7.50	78.82	20.89	0.29
Spruce	7.66	79.87	19.92	0.21
Pellets*	8.22	77.39	21.35	1.26

* Pellets also contains: 0.21 mg·kg^{-1} As, 0.03 mg·kg^{-1} Cd, 0.27 mg·kg^{-1} Cr, 1.81 mg·kg^{-1} Cu, 0.3 mg·kg^{1} Pb, 15.94 mg·kg^{-1} Zn, 0.013 mg·kg^{-1} Hg, 151 mg·kg^{-1} Cl.

As it is documented in table 4.4, the wood contains moisture, high content of volatilises, some content of fixed carbon and very low content of ash. If we assume that the main components of biomass are carbon, hydrogen and oxygen (as it is documented in table 4.5) and the main components of blowing air are oxygen and nitrogen with low concentration of water vapour, the wood combustion/gasification process can be schematically described by the diagram illustrated in figure 4.2.

Table 4.5. The basic physicochemical data for "hard" and "soft" wood

Wood	Density ($kg \cdot m^{-3}$)	q_v ($kJ \cdot kg^{-1}$)	q_n ($kJ \cdot kg^{-1}$)	W (wt.%)	Chemical composition (wt.%)			
					C	H	O	N
Oak	654.4	18 800	14 100	20	50.1	6.2	42.5	1.2
Spruce	623.7	20 600	13 800	20	50.0	6.2	41.9	0.9

W – moisture, the optimum moisture for biomass gasification varies from 15 to 35%.

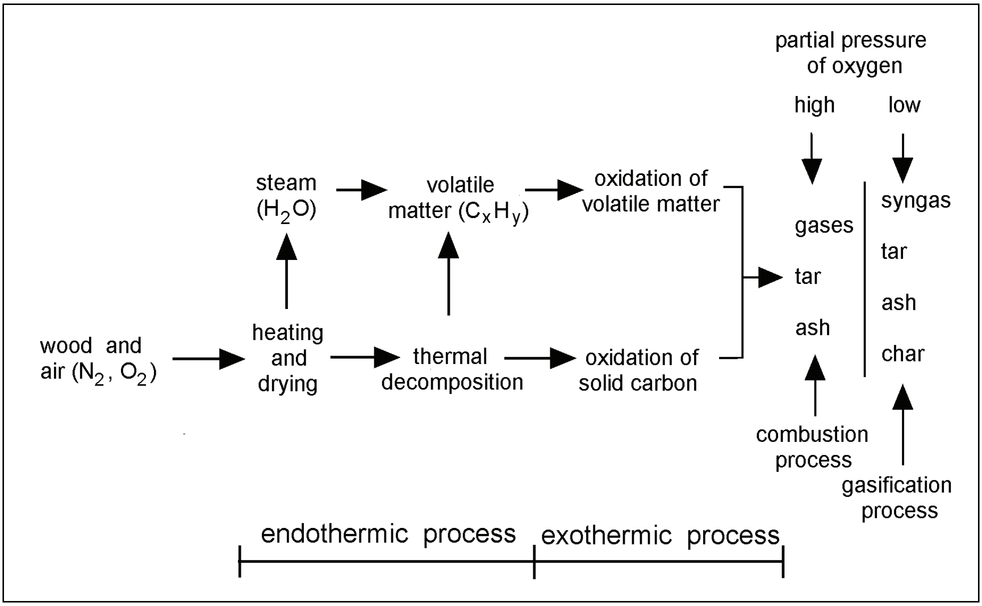


Fig. 4.2. Schematic illustration of a combustion/gasification process

The products from a combustion/gasification process are gas phase – combustion gases (offgas), syngas with tar, and solid phase – ash or ash and char.

The mains components of combustion gases are carbon dioxide (CO_2), water steam ($H_2O_{(g)}$) and nitrogen (N_2), but they also have low concentration of unreacted excess of oxygen and some harmful minor components such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), organic compounds such as PAH (polycyclic aromatik hydrocarbons), dioxins and furans [5].

The organic compounds, produced under thermal or partial-oxidation regime of biomass, are called tars. It is generally assumed that tar is a mixture of hydrocarbons and oxygen with high molecular weights and high boiling points which start to condense at 80 °C [6–8]. The main tar's components, produced under thermal decomposition of biomas, are phenol (C_6H_6O), indene (C_9H_8), naphthalene ($C_{10}H_8$), methylnaphthalene ($C_{11}H_{10}$), acenaphtylene ($C_{12}H_8$), fluorene ($C_{13}H_{10}$) and pyrene ($C_{16}H_{10}$) [9–12]. Figure 4.3 shows the transition, as a function of the process temperature, from the primary products to phenolic compounds and aromatic hydrocarbons [6]. The relationship between the yield of tars and the reaction temperature are documented in figure 4.4 [6].

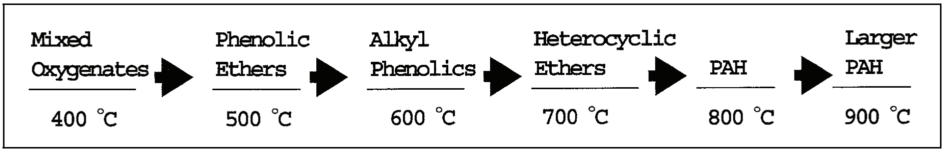


Fig. 4.3. Tar maturation scheme proposed by Elliott [6]

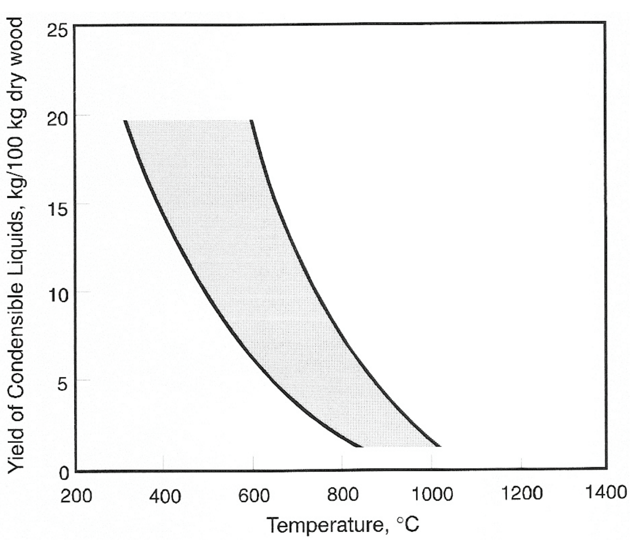


Fig. 4.4. Tar yield as a function of the maximum temperature exposure [6]

Tar yield is controlled by a number of competitive formation and decomposition reactions, which depends on the residence time, temperature and gas composition. In general, as is documented in fig. 4.4, low temperatures favour the formation of more tars. The high partial pressure of oxygen in the gas phase, depending on the temperature and residence time, decreases the tars content in the offgas or in the syngas [1].

The ash is the unburning inorganic residue that remains after biomass combustion is completed. The ash amount from solid wood combustion is very low and varies from 0.2 wt.% to 1.5 wt.%, but from 3 to 7 wt.% when the bark is burned. Typical values for wood's ash, such as chemical composition and sintering and melting points, are summarized in tab. 4.6 [13]. The wood's ash gasification process has usually some amount of unreacted charcoal/char (fig. 3.5), which decreases the energy recovery from biomass. Another problem of the ash, obtained from biomass, is the relatively high concentration of alkaline, which decreasing the ash sintering and melting points, as can be predicted from ternary diagram CaO-SiO_2-Na_2O presented in fig. 4.6 [13].

Table 4.6. Typical wood ash composition [13]

Component	Unit	Wood
SiO_2	wt.%	15.2
Al_2O_3	wt.%	2.65
TiO_2	wt.%	0.26
Fe_2O_3	wt.%	3.8
CaO	wt.%	37.3
MgO	wt.%	8.5
SO_3	wt.%	3.0
Na_2O	wt.%	3.0
K_2O	wt.%	8.6
P_2O_5	wt.%	13.7
Sintering point	°C	1180–1270
Melting point	°C	1521–1600

During the combustion/gasification process, the endothermic and endothermic processes take place in the reactor. The heating, drying and thermal decomposition of wood, under the wood ignition temperature, are endothermic processes and the oxidation of volatile matter and solid carbon over wood ignition temperature are exothermic ones. The factor, limiting combustion or gasification process, is partial pressure of oxygen in the system. If the partial pressure of oxygen in the system is high, the combustion process takes place and the products of combustion process are solid residue – ash and offgas with high concentration of carbon dioxide, and steam with low concentration of tar. However, if the partial pressure of oxygen is low, the autotherm gasification process takes place and the products of gasification process are solid residue – ash with some contents of charcoal and syngas with high concentration of carbon monoxide and hydrogen with variable tar concentration and low concentration of carbon dioxide.

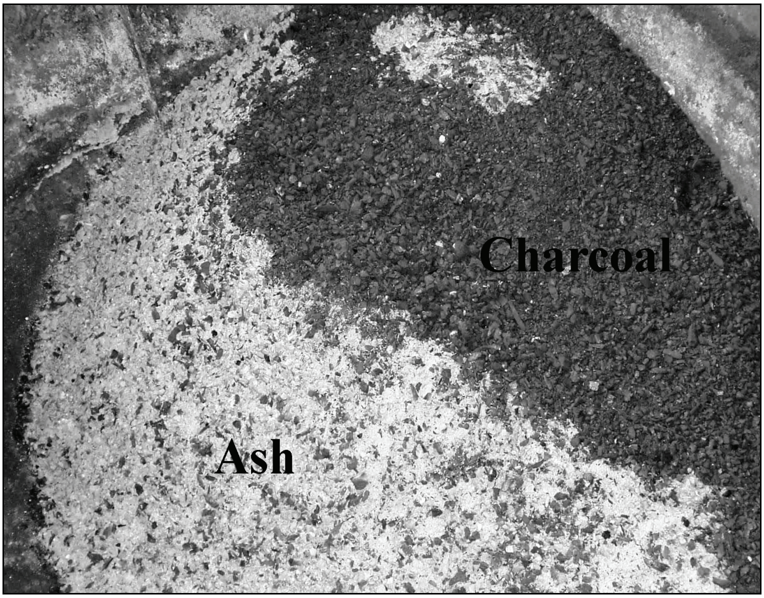
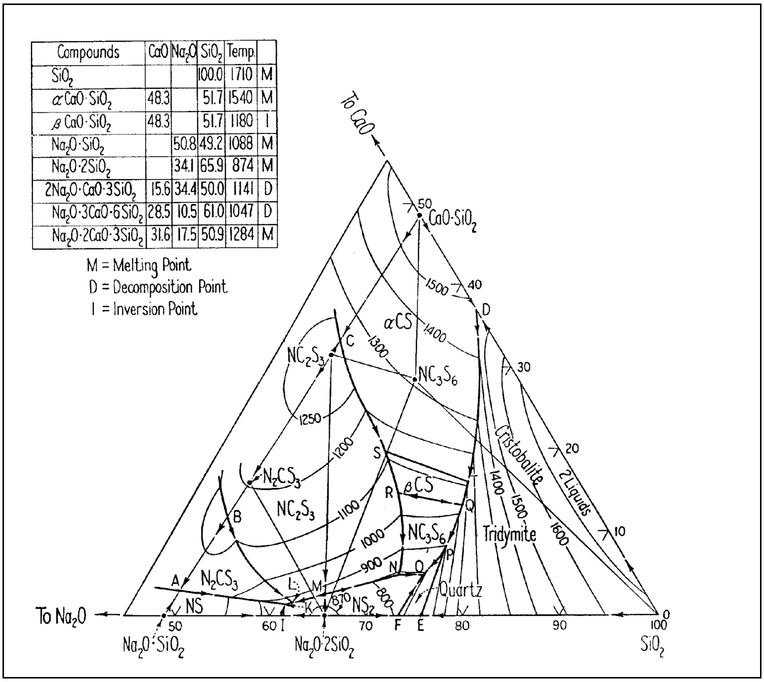


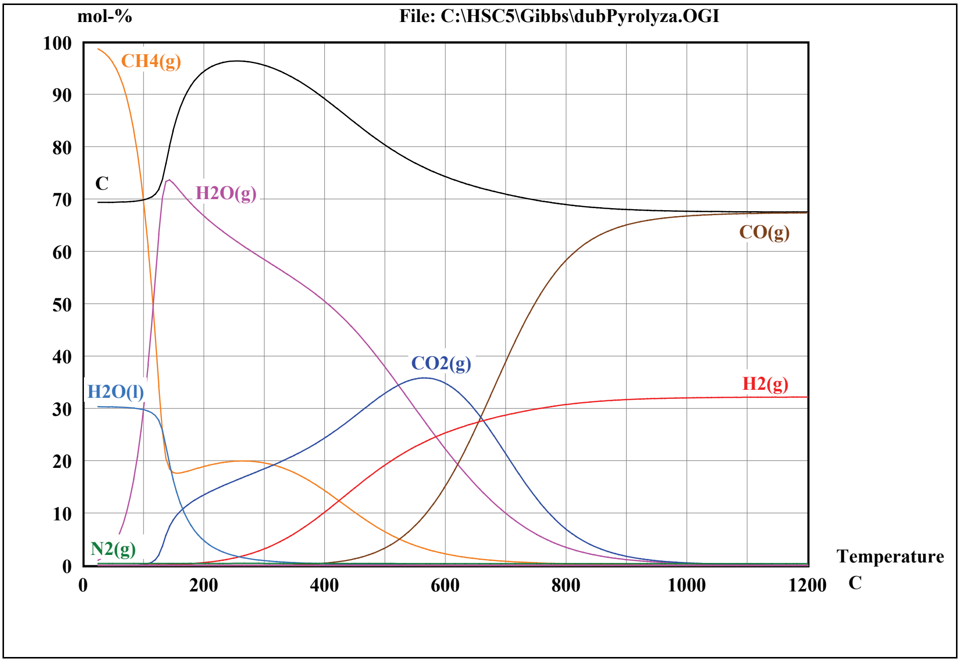
Fig. 4.5. Photograph of wood ash with unreacted charcoal



Compounds	CaO	Na_2O	SiO_2	Temp.	
SiO_2			100.0	1710	M
α $CaO \cdot SiO_2$	48.3		51.7	1540	M
β $CaO \cdot SiO_2$	48.3		51.7	1180	I
$Na_2O \cdot SiO_2$		50.8	49.2	1088	M
$Na_2O \cdot 2SiO_2$		34.1	65.9	874	M
$2Na_2O \cdot CaO \cdot 3SiO_2$	15.6	34.4	50.0	1141	D
$Na_2O \cdot 3CaO \cdot 6SiO_2$	28.5	10.5	61.0	1047	D
$Na_2O \cdot 2CaO \cdot 3SiO_2$	31.6	17.5	50.9	1284	M

M = Melting Point
D = Decomposition Point
I = Inversion Point

Fig. 4.6. Ternary diagram CaO-SiO$_2$-Na$_2$O [14]



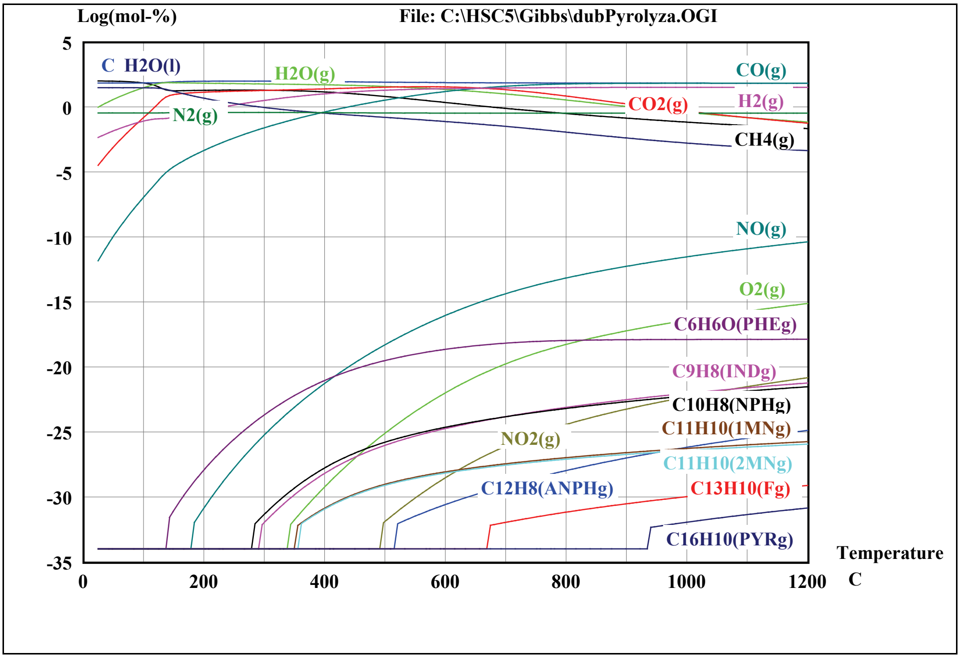


Fig. 4.7. The composition of syngas vs. the temperature the during oak wood gasification process

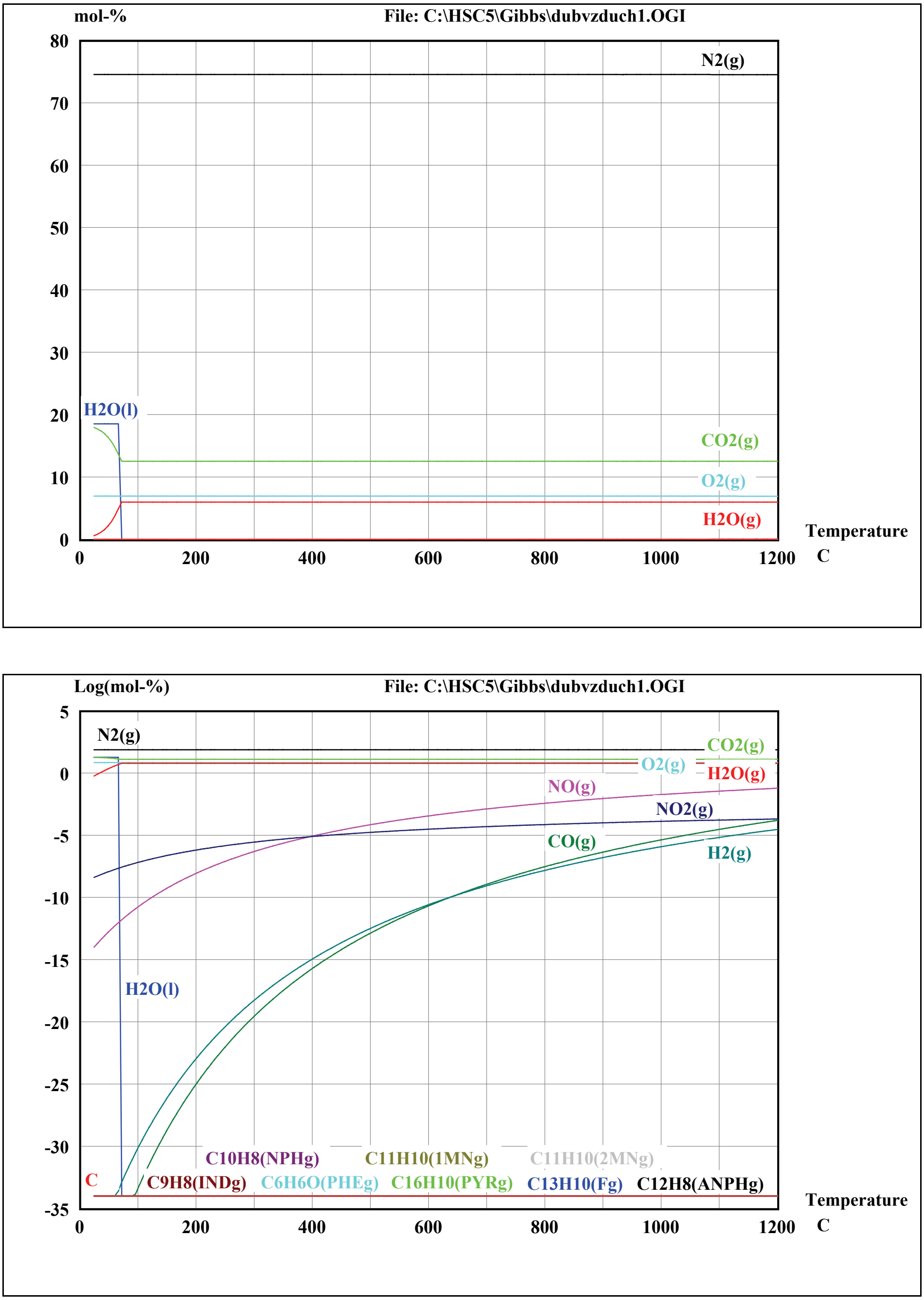


Fig. 4.8. The composition of gas vs. the temperature during the oak wood combustion process

To verify these assumptions the simulation of wood combustion in air and wood gasification in nitrogen has been done by free energy minimization method, using the thermodynamic package HSC Chemistry [15]. For the simulation, it was suggested that oak wood, with moisture 7.5 hm% and chemical composition documented in tab. 4.5, to be heated up to the temperature of 1200 °C without air – the gasification process, and with air – the combustion process [16]. Some results of the gas phase composition versus the temperature for the oak wood combustion and gasification are illustrated in figs. 4.7 and 4.8.

Between carbon and oxygen the following heterogeneous reactions occur [17]:

$$C_{(s)} + O_{2\,(g)} = CO_{2(g)} \quad \Delta G_1^\circ = -394\,100 - 0.8\ T \quad (J{\cdot}mol^{-1}) \tag{4.1}$$

$$2C_{(s)} + O_{2(g)} = 2CO_{2(g)} \quad \Delta G_2^\circ = -223\,400 - 175.3\ T \quad (J{\cdot}mol^{-1}) \tag{4.2}$$

By subtraction of reactions (4.1) and (4.2), the Boudouard reaction is obtained:

$$CO_{2(s)} + C_{(s)} = 2CO_{2(g)} \quad \Delta G_3^\circ = -170\,700 - 174.5\ T \quad (J{\cdot}mol^{-1}) \tag{4.3}$$

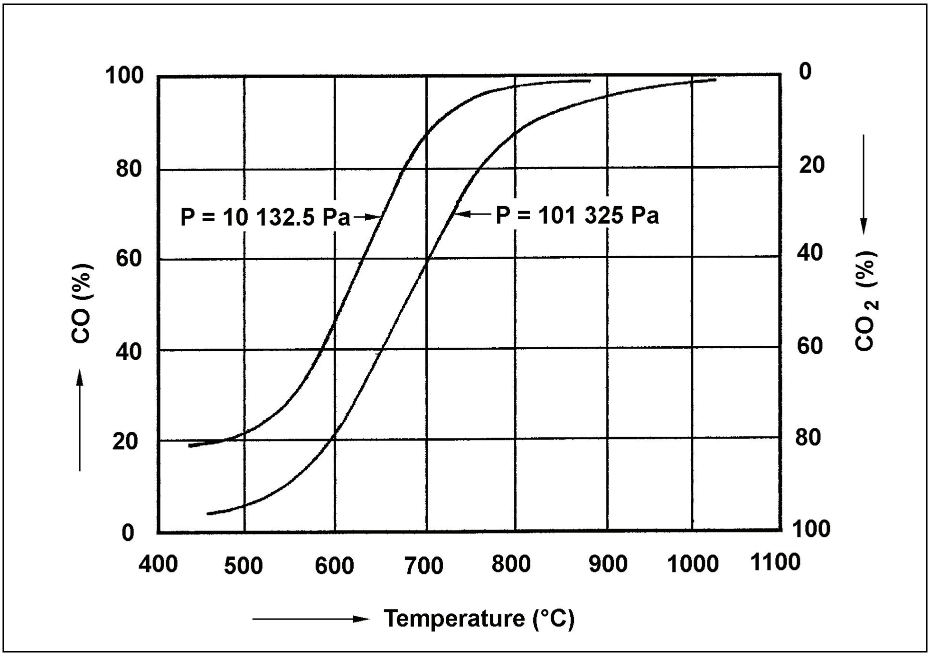


Fig. 4.9. The gas composition for the Boudouard reaction versus the temperature for different total gas pressures

The reactions (4.1) and (4.2) are exothermic and the Boudouard reaction (4.3) is endothermic. The gas composition for the Boudouard reaction versus the temperature for different total gas pressures is illustrated in fig. 4.9.

From figures 4.7, 4.8 and 4.9 result that the reaction (4.1) dominates at a lower temperature and higher partial pressure of oxygen. The reactions (4.2) and (4.3) are important at a higher temperature and oxygen deficiency, but the chemical rate of reaction (4.1) is one hundred times higher as for the reaction (4.3) [18]. This means that the reaction (4.3) depends not only on the temperature, as is documented in fig. 4.9, but also on the contact time on the syngas from carbon.

The syngas, obtained by blowing with air, has a high nitrogen content and consequently a low calorific value, so to obtain a richer syngas, steam is usually added to the blast. Steam reacts with the carbon from biomass, according to the reaction [17]:

$$H_2O_{(g)} + C_{(s)} = H_{2(g)} + CO_{(g)} \quad \Delta G_4^\circ = -134\,700 - 142.5\,T \quad (J\cdot mol^{-1}) \qquad (4.4)$$

Since the steam is free of nitrogen, the obtained syngas will be richer in combustibles and have a higher calorific value than without the steamThe reaction (4.4) is strongly endothermic, and the steam addition lowers the temperature in the gasifier. This means that by the steam addition, some physical enthalpy for steam production is needed, but this heat is converted into useful chemical enthalpy of syngas. The heat balance of gasification process using steam for syngas production can be improved by preheated air, or by oxygen-enriched air, or by necessary heat supply by electricity, or by a part of syngas combustion.

The following conclusion for biomass gasification process can be made:

- The composition and the heating value of the syngas depend on the type of gasifier.
- The composition and the heating value of the syngas strongly depend on the heat transfer, temperature and gasification agent.
- The air blowing into direct heating gasifier will increase nitrogen content and decrease calorific value of syngas.
- The oxygen-enriched air or pure oxygen blowing into direct heating gasifier will generate a medium calorific syngas.
- The steam blowing into gasifier will generate a medium calorific syngas, but the external heat for gasification process is needed.
- The heat balance of gasification process can be improved by preheated air, or by oxygen-enriched air, or by the necessary heat supply by electricity, or by a part of syngas combustion.
- The tar concentration in syngas decreases if the gasification temperature increases.

- Unreacted charcoal in the ash decreases the energy recovery from biomass during the gasification process.

4.3. The wood combustion process

The effect of temperature on the wood combustion in air atmosphere was studied by the high temperature microscope LEITZ Wetzlar, which is shown in fig. 4.10 [19]. The samples of oak and spruce solid wood (fig. 4.11) and the sample of wood pellet, with the composition summarized in tabs. 4.4 and 4.5 were slowly heated, in the air atmosphere, in the electric furnace of high temperature microscope (fig. 4.12). During the heating process, the profile of samples was being monitored by Olympus digital camera. The results of the digital pictures taken at different temperatures with the comparative lattice of 0.5 × 0.5 mm are presented in figs. 4.13, 4.14 and 4.15.

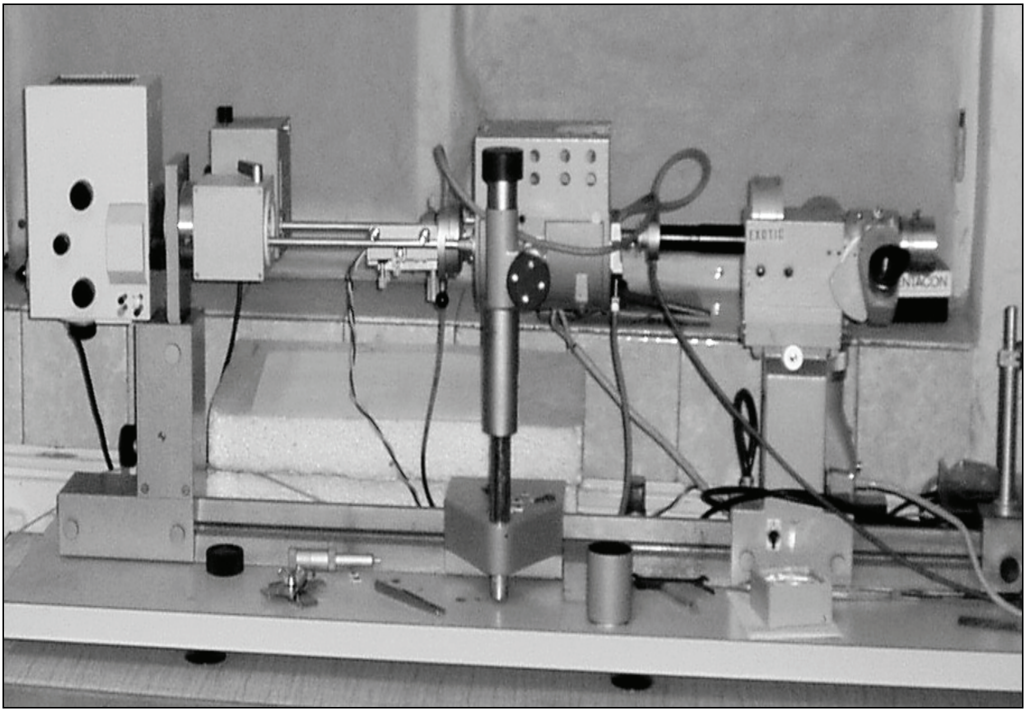


Fig. 4.10. The view of the high temperature microscope LEITZ Wetzlar

Fig. 4.11. The view of the wood sample before charging it into the electric furnace

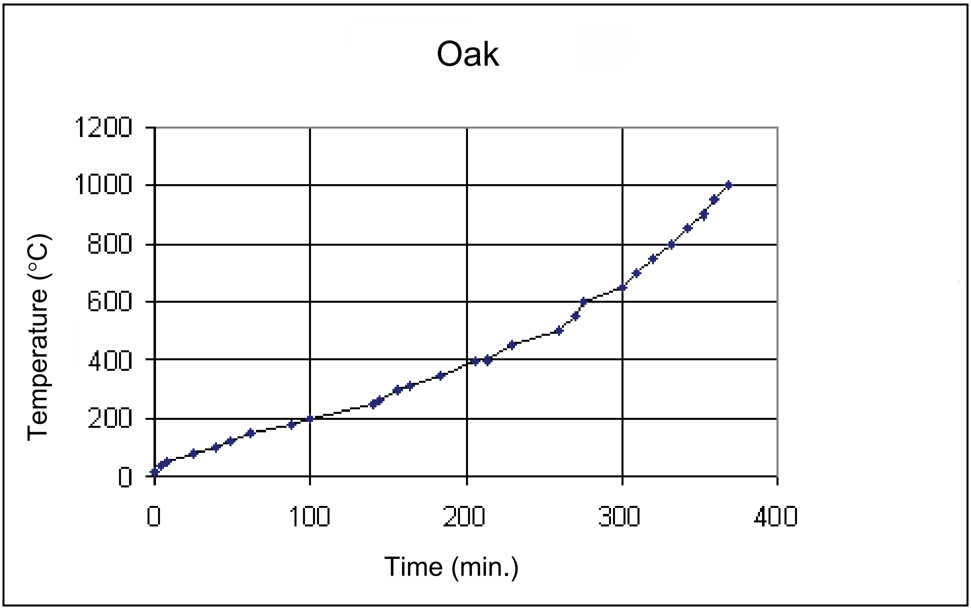


Fig. 4.12. The heating rate example of the wood sample in the electric furnace of the high temperature microscope in the air

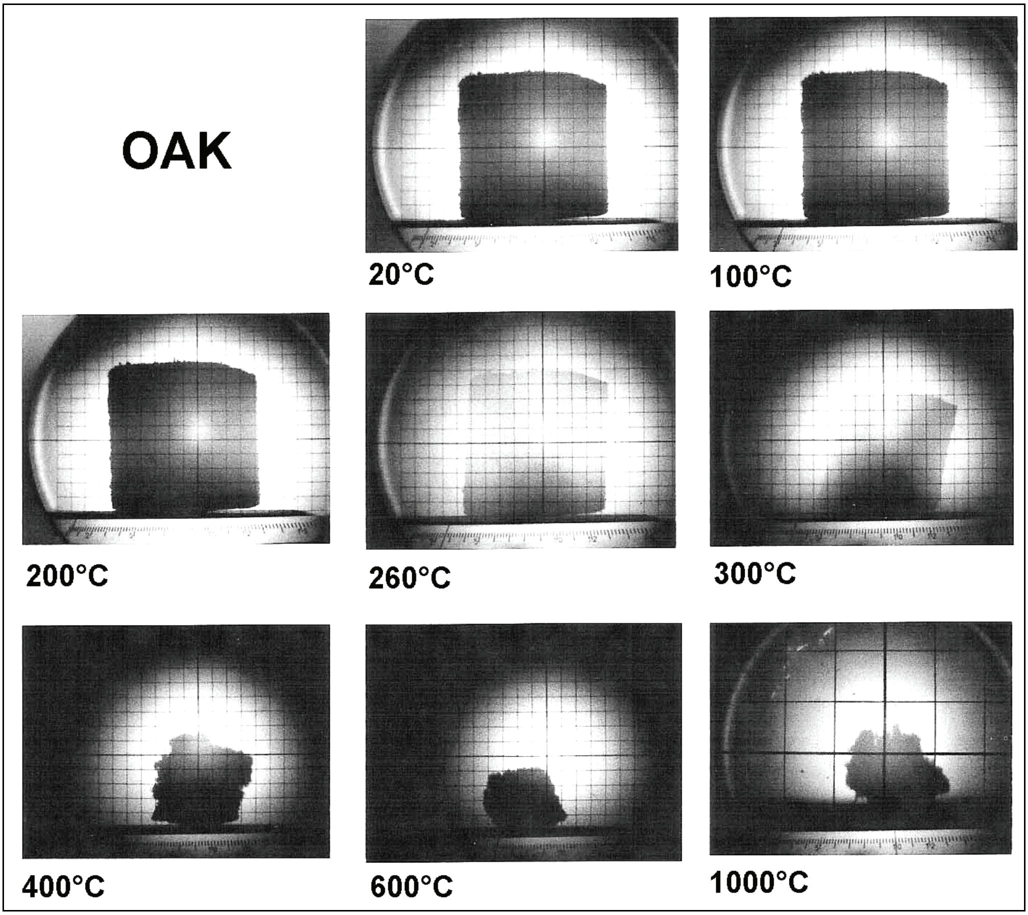


Fig. 4.13. The temperature effect on the profile geometry
of the oak solid wood heated in air

The result presented in fig. 4.13 for the “hard” oak solid wood sample shows that:

- Moisture was evaporated in the temperature range from 20 to 260 °C.
- Volatile was released in the temperature range from 260 to 400 °C.
- At 400 °C only compact char particle – solid carbon with ash, was presented.
- In the temperature range from 400 to 1000 °C the compact char particle with relatively small surface was slowly oxidized by air according to the heterogeneous oxidation mechanism.

At the temperature of 1000 °C only the ash, with very low concentration of non-combustion solid carbon, was presented.

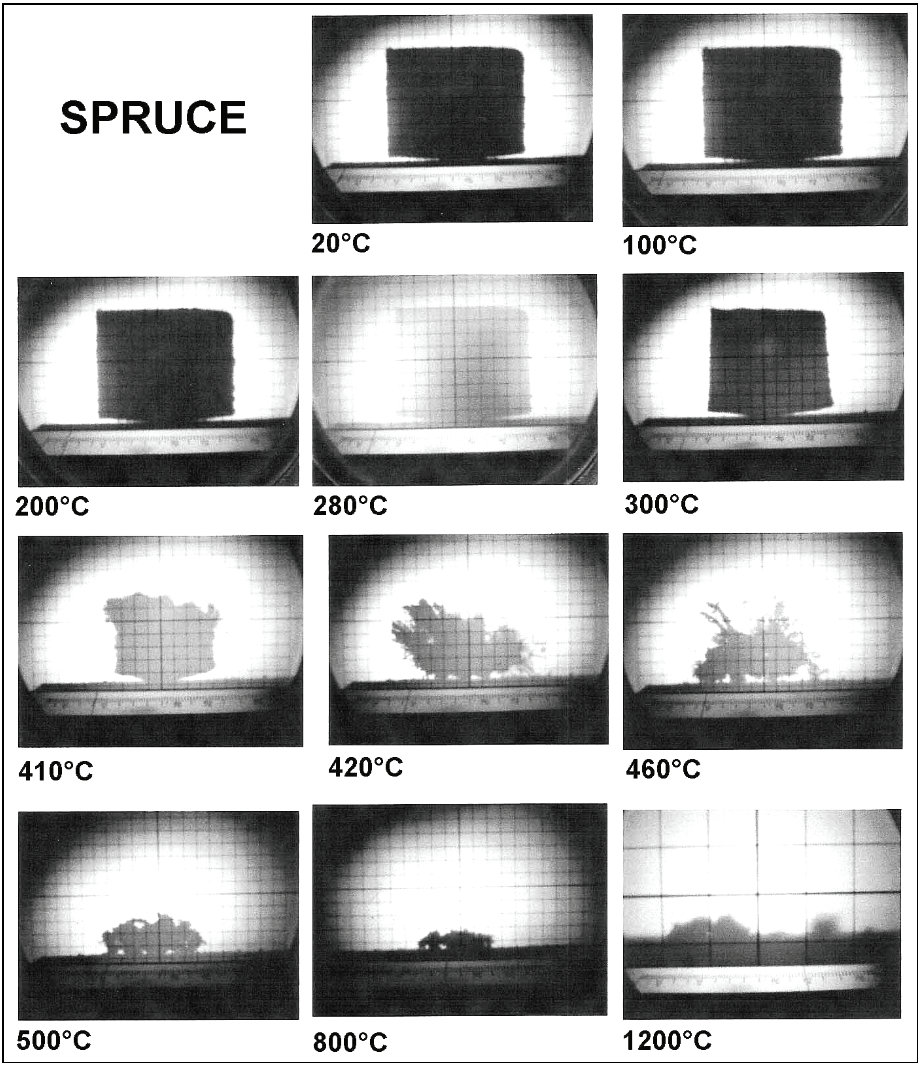


Fig. 4.14. The temperature effect on the profile geometry of the spruce wood heated in air

The result presented in fig. 4.14 for the “soft” spruce solid wood sample shows that:

- Moisture was evaporated in the temperature range from 20 to 280 °C.
- Volatile was released in the temperature range from 280 to 410 °C.
- At 410 °C char particle – solid carbon with ash, was disintegrated into fine fibrous char.
- In the temperature range from 410 to 500 °C the main amount of very fine fibrous char with very large surface area was rapidly oxidized by air.

- In the temperature range from 500 to 1200 °C very little of char was oxidized by air.
- At the temperature of 1200 °C only the ash was presented. No carbon content in the ash was detected.

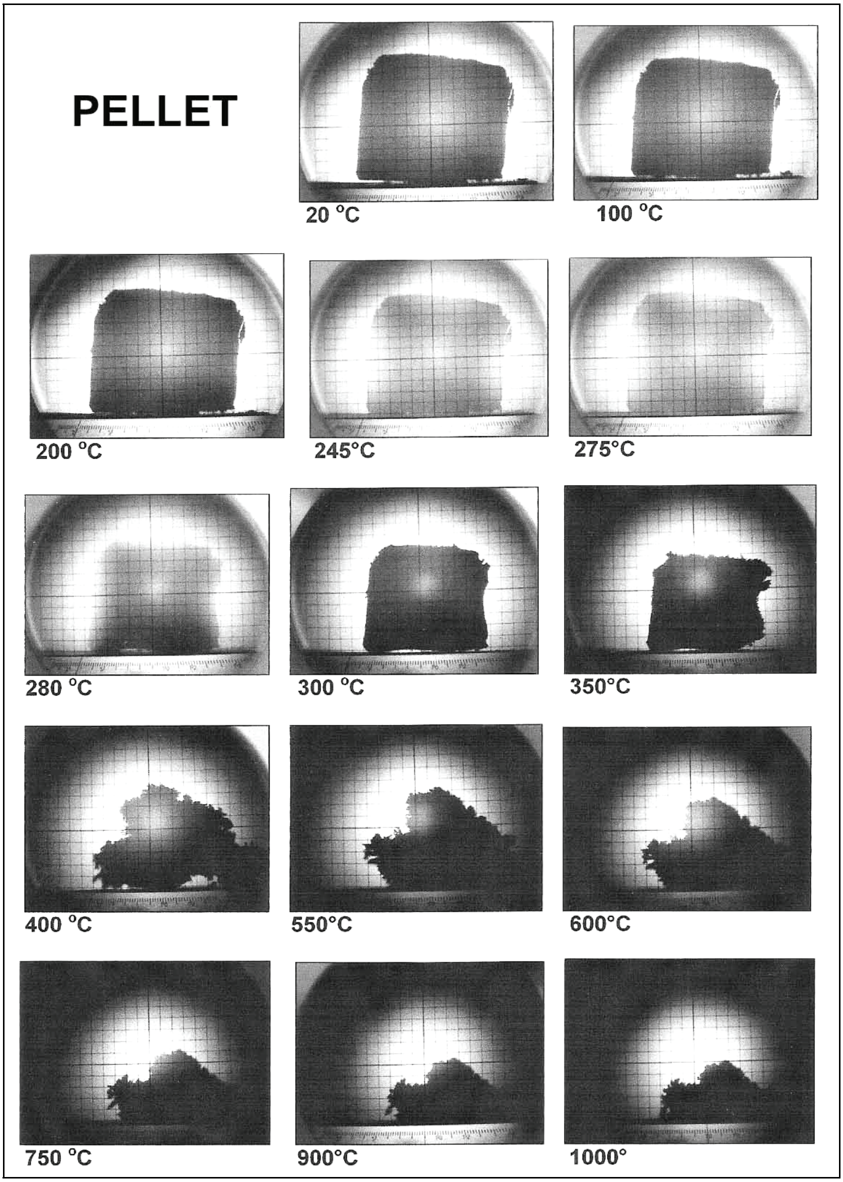


Fig. 4.15. The temperature effect on the profile geometry of the sample from wood pellet heated in air

The result presented in fig. 4.15 for the sample from wood pellet shows that:

- Moisture was evaporated in the temperature range from 20 to 245 °C.
- Volatile was released in the temperature range from 245 to 280 °C.
- At 300 °C only compact char particle – solid carbon with ash, was presented.
- In the temperature range from 300 to 1000 °C the compact char particle with relatively small surface was slowly oxidized by air by heterogeneous oxidation mechanism.

At the temperature of 1000 °C only the ash with very low concentration of non-combustion solid carbon was presented.

Fig. 4.16. Spruce wood chips

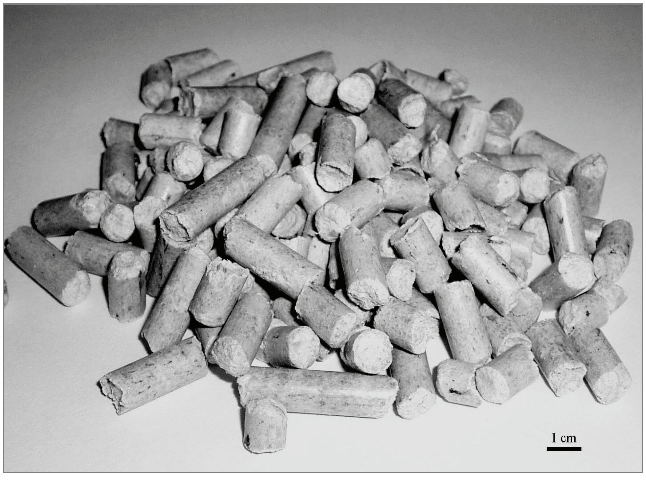


Fig. 4.17. Wood pellets

The weight losses of samples – spruce wood chips (fig. 4.16) and wood pellets (fig. 4.17), during combustion in air, were studied by the laboratory gravimetric furnace Nabertherm L9/11SW/B170. The results are presented in figs. 4.18 and 4.19.

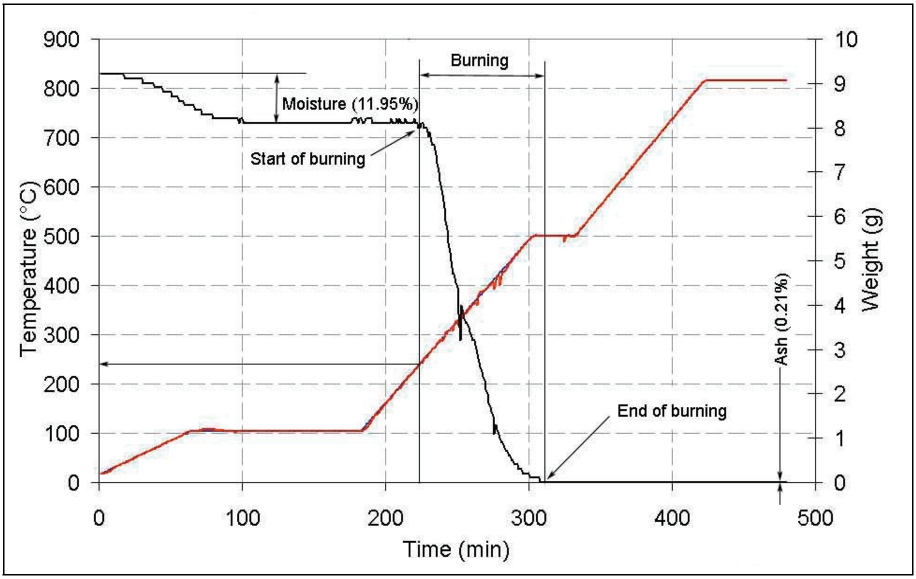


Fig. 4.18. The weight loss of the spruce wood chips sample during the combustion in air

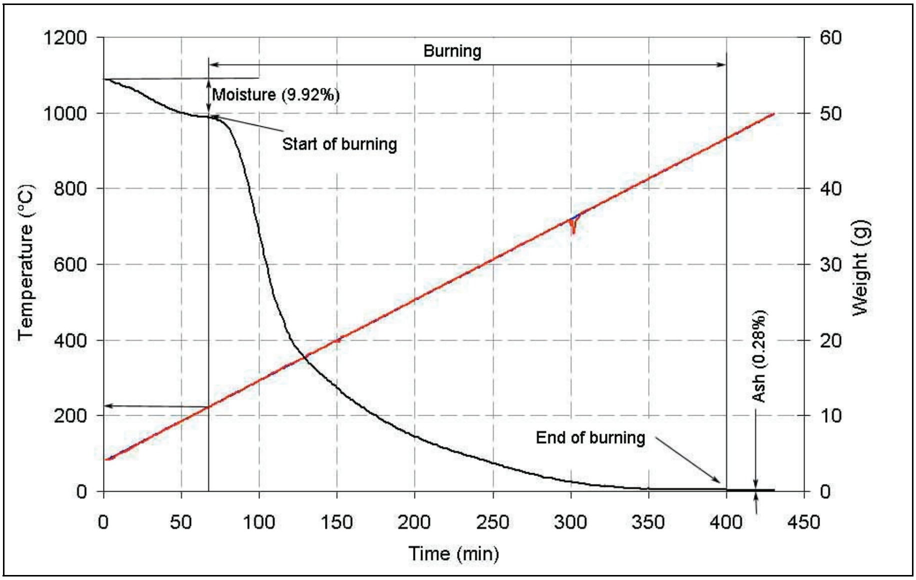


Fig. 4.19. The weight loss of the wood pellets sample during the combustion in air

The result presented in figs. 4.18 and 4.19 shows, that in the temperature range from 20 to 245/220 °C the spruce wood chips and pellets were drying. The spruce wood chips were burnt out in the temperature range from 245 to 500 °C and the pellets in the temperature range from 220 to 945 °C. The ash content in both samples was very low – 0.21 wt.% from the spruce wood chips and 0.28 wt.% from the wood pellets. From the thermodynamic analysis and laboratory study of the wood combustion mechanism in the air, the following conclusion can be made, and the main factors, which influence the wood combustion process, can be summarised in the following points:

- Wood has high moisture content, which can be maximum 50 wt.% on a wet basis.
- Moisture is evaporated in the temperature range from 20 to 245 °C.
- Wood has high content of volatiles which is until 79.87 wt.% in dry bases.
- Volatile is released in the temperature range from 245 to 410 °C.
- The homogeneous oxidation of volatiles is influenced by oxygen diffusion inside the flame.
- Hard wood – oak and wood pellets form compact char particles with relatively small surface at the temperature range from 350 to 400 °C, and the fixed carbon oxidize slowly by heterogeneous mechanism and non-combustion solid carbon in ash is present at temperature of 1000 °C.
- Soft wood – spruce form fibrous char with a large reactive surface, so the oxidation/combustion runs so fast that it is finished at the temperature of about 500 °C.

4.4. The wood gasification process

The preliminary laboratory pyrolysis tests with solid oak wood at 900 °C in nitrogen atmosphere showed that from 1 kg of solid oak wood with moisture content of about 12 wt.% 0.128 kg of charcoal and 0.68 Nm^3 syngas with chemical composition can be obtained as summarized in table 4.7 [20].

For the study of the high temperature wood gasification process, plasma technology was used. Plasma technology, commonly used in metallurgy, is the only possible way for energy recovery from biomass and from municipal solid waste from a viewpoint of environmental protection and recycling of resources [21].

This technology, schematically presented in figure 4.20 [22], has been adapted for the high temperature biomass gasification process.

In plasma reactor the biomass, which can be described by a general chemical formula – $C_6H_{10}O_5$, will be transformed, by thermal decomposition, into high energetic syngas with high concentration of hydrogen and carbon monoxide and very low concentration of tars, which can be used after cleaning from dusts particles for energy production. To improve carbon recovery for the gasification process, the steam as plasma forming gas can be used. The non-combustible ash will be transformed into inert slag, which can be used in civil engineering.

Table 4.7. Chromatograph analysis of syngas (dry bases) from solid oak wood pyrolysis at 900 °C [20]

Compound	Unit	Oak wood
Hydrogen (H_2)	vol.%	38.10
Carbon monoxide (CO)	vol.%	22.60
Carbon dioxide (CO_2)	vol.%	13.45
Methane (CH_4)	vol.%	4.87
Ethylene (C_2H_4)	vol.%	0.19
Ethane (C_2H_6)	vol.%	0.42
Acetylene (C_2H_2)	vol.%	<0.001
$C_{5\text{-}8}$	vol.%	0.07
C_4	vol.%	0.10
C_3	vol.%	0.20
Oxygen (O_2)	vol.%	0.50
Nitrogen (N_2)	vol.%	19.50
Calorific value	$MJ\cdot m^{-3}$	9.50

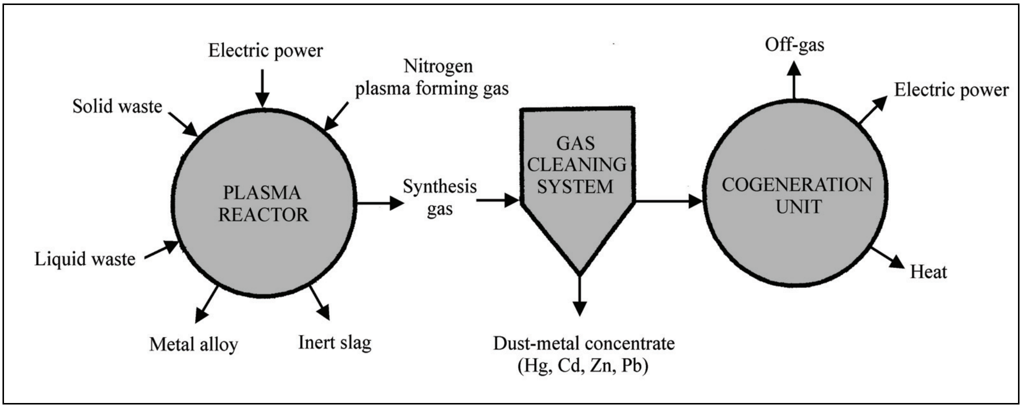


Fig. 4.20. Flow sheet proposed for processing of municipal solid waste by the plasma gasification and smelting process [22]

The preliminary test, for the high temperature gasification process, has been studied in two types of plasma reactors. One type of experiments have been done in the laboratory 3 kVA DC transferred plasma arc reactor (fig. 4.21) and the second type of experiments have been done in the 30 kVA DC transferred plasma arc pilot reactor (fig. 4.22).

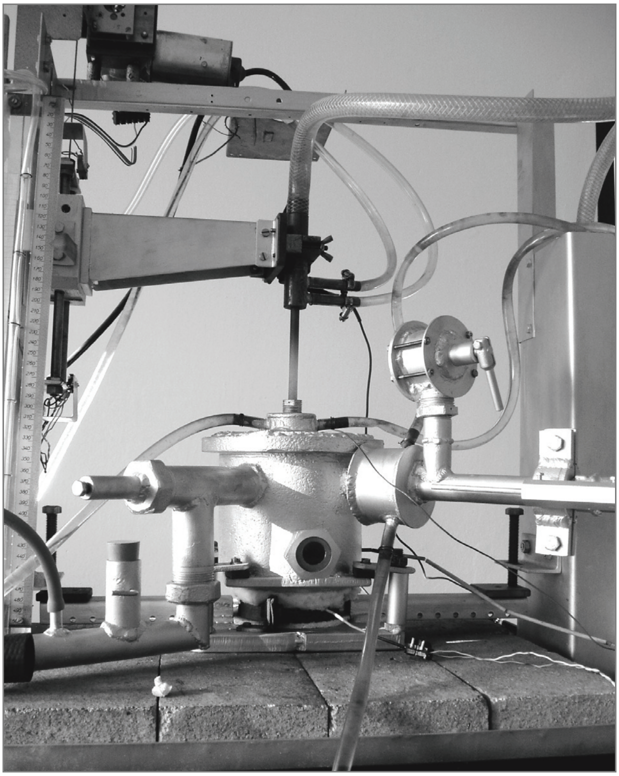


Fig. 4.21. Laboratory scale 3 kVA DC

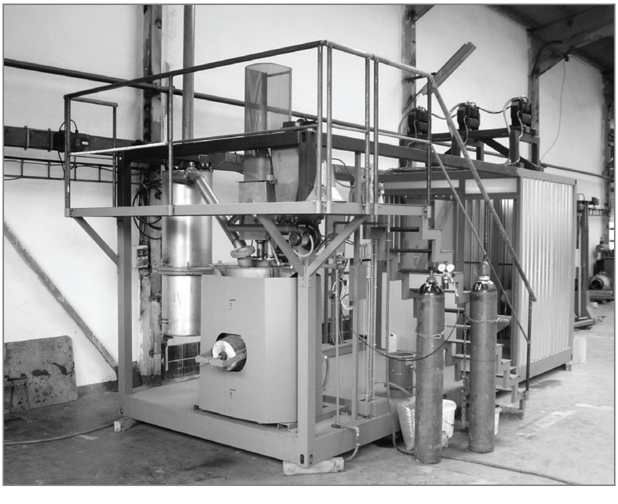


Fig. 4.22. 30 kVA DC transferred plasma arc pilot reactor
transferred plasma arc reactor

The syngas with composition, summarized in tab. 4.8, was obtained by the plasma gasification of solid oak wood samples in the laboratory 3 kVA DC transferred plasma arc reactor in nitrogen atmosphere at the temperature of 1600 °C, described elsewhere [21].

Table 4.8. Chromatograph analysis of syngas (dry bases) obtained from the gasification of solid oak wood in the laboratory plasma reactor at 1600 °C [21]

Compound	Unit	Oak wood
Hydrogen (H_2)	vol.%	5.40
Carbon monoxide (CO)	vol.%	0.40
Carbon dioxide (CO_2)	vol.%	0.70
Methane (CH_4)	vol.%	1.69
Ethylene (C_2H_4)	vol.%	0.061
Ethane (C_2H_6)	vol.%	0.051
Acetylene (C_2H_2)	vol.%	7.45
$C_{5\text{-}8}$	vol.%	0.020
C_4	vol.%	0.025
C_3	vol.%	0.053
Oxygen (O_2)	vol.%	3.54
Nitrogen (N_2)	vol.%	80.60
Calorific value	$MJ{\cdot}m^{-3}$	2.546

The preliminary tests, with the gasification of solid oak wood samples in the laboratory scale DC transferred plasma arc reactor, show that the main energetically useful components of syngas, summarized in tab. 4.8, are hydrogen, methane and acetylene. It should be noted that, due to low amount of the oak wood samples charged into the plasma reactor and high flow rate of plasma forming nitrogen gas (the flow rate of plasma forming nitrogen gas was 5.5 $dm^3{\cdot}min^{-1}$ and the charge of solid oak wood samples varied from 2.5 to 5 g), the nitrogen content in the resulted syngas was high, and the concentration of combustibles components was relatively low. This means that the calorific value of syngas diluted by nitrogen was very low too. Increasing of the calorific value of syngas is possible by a continuous gasification process, where the ratio between amounts of wood charging into the plasma reactor and the flow rate of plasma forming nitrogen gas may be very low. This means that the syngas will have higher concentration of combustibles components and lower concentration of nitrogen. To verify this suggestion, the continuous batch tests were run in the 30 kVA DC transferred plasma arc pilot reactor. The singas composition obtained during the gasification of spruce wood chips in the pilot plasma reactor at the temperature of 1400 °C is summarized in tab. 4.9. The results from the gasification tests in the pilot plasma reactor show that by a continuous gasification process of wood, the syngas with high concentration of hydrogen and carbon monoxide with low concentration of tars (components C_3, C_4, C_{5-8} in tab. 4.9) with a medium calorific value can be obtained.

Table 4.9. Chromatograph analysis of syngas (dry bases) obtained from gasification of spruce wood chips in the pilot plasma reactor at 1400 °C

Compound	Unit	Spruce wood
Hydrogen (H_2)	vol.%	28.60
Carbon monoxide (CO)	vol.%	35.10
Carbon dioxide (CO_2)	vol.%	3.70
Methane (CH_4)	vol.%	5.83
Ethylene (C_2H_4)	vol.%	0.84
Ethane (C_2H_6)	vol.%	0.042
Acetylene (C_2H_2)	vol.%	0.26
$C_{5\text{-}8}$	vol.%	0.006
C_4	vol.%	0.016
C_3	vol.%	0.07
Oxygen (O_2)	vol.%	1.39
Nitrogen (N_2)	vol.%	24.10
Calorific value	$MJ \cdot m^{-3}$	10.41

The thermodynamic calculation and laboratory tests of wood gasification show that:

- The low temperature gasification process produces the low calorific value syngas with the low concentration of carbon monoxide and high concentration of carbon dioxide and tars, and high content of char in the ash.
- The high temperature gasification process produces the medium calorific value syngas with a relatively higher concentration of carbon monoxide and lower concentration of carbon dioxide, with tar absence and the slag with low or non-content of carbon.
- The highest calorific value of the syngas, strongly depends on the gasification agent. From the theoretical point of view, the calorific value of syngas from the high temperature wood gasification process can be increased by using the steam as the plasma forming gas, but because the reaction (4.4) is strongly endothermic, the steam addition into the plasma reactor will increase the electric power consumption of the gasification process.

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Chapter 5

Hydrogen – fuel for the future; fuel cell

Over a period of millions of years fossil fuels have been naturally formed from the remains of animals and plants that lived 300 to 400 million years ago. Current consumption rates are many orders of magnitudes higher than historic fossil fuel formation rates. Consequently, the use of fossil fuel is not sustainable over longer periods of time. In the long term other primary energy carriers will need to replace fossil fuels. It is uncertain whether this transition will take place before fossil fuels (especially oil reserves) are exhausted.

5.1. Introduction

Simply replacing fossil fuels with renewable energy sources (without the introduction of a new secondary energy carrier) will result in a system with significantly reduced flexibility. This system will not be able to compensate for differences between supply and demand to the same degree as the current fossil fuel based energy supply system.

The two main reasons are:

- biomass is, due to its solid form and relatively low heating value, not well suited for large-scale distribution to the end-user,
- no large-scale electricity storage media is readily available.

A choice of secondary energy carriers exists the examples are: methanol, biogas, bio-oil, bio-diesel, and hydrogen. Hydrogen is the most versatile of these for several reasons, such as:

- hydrogen can be produced from virtually all other energy carriers,
- hydrogen offers possibilities of electricity storage,
- hydrogen allows virtually emission-free end-use.

None of other secondary energy carriers offers all of the advantages mentioned above. This does not mean other energy carriers are not viable for specific applications, but it indicates that hydrogen is the only energy carrier that bears the potential to solve the future energy supply challenges on a global scale.

Hydrogen is the most abundant element in the universe. And while it doesn't exist by itself on Earth, it can be produced from a wide variety of resources – coal, oil, natural gas, biomass, and water. This versatility contributes to the promise of hydrogen, allowing it to be produced where and when we need it. About 95% of the hydrogen we use today comes from the reforming of natural gas. The remainder, high-purity hydrogen from water electrolysis, is primarily produced using electricity generated by burning fossil fuels. But to realize the full benefits of a hydrogen economy – sustainability, increased energy security, diverse energy supply, reduced air pollution and greenhouse gas emissions – hydrogen must be produced cleanly, efficiently, and affordably from domestically available renewable resources.

5.2. Production of hydrogen

Hydrogen is commonly produced by extraction from hydrocarbon fossil fuels via a chemical path:

- H_2 produced from fossil fuels with **C**O_2 **C**apture and **S**torage (CCS);
- Significant H_2 production from renewable sources, including biomass gasification;
- Increasing de-carbonization of fossil fuel enhanced by H_2 production.

Hydrogen may also be extracted from water:

- via biological production in an algae bioreactor,
- using electricity (by electrolysis),
- chemicals (by chemical reduction),
- heat (by thermolysis); these methods are less developed for bulk generation in comparison to chemical paths derived from hydrocarbons.

H_2 produced by steam reforming of natural gas or others hydrocarbons

- catalytic reactions at 700–1000 °C, pressure 3–25 bar
  endothermic reactions: ΔH^0_{298}, kJ/mol

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \qquad 206 \qquad (5.1)$$

$$CH_4 + CO_2 \rightarrow 2\ CO + 2\ H_2 \qquad 247 \qquad (5.2)$$

Next water-shift reaction – exothermic reaction (at 370 °C):

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad -41 \qquad (5.3)$$

Direct thermal cracking of methane

$$CH_4 \rightarrow C + 2H_2 \quad \Delta H \qquad 75 \tag{5.4}$$

Gasification of solid fuel including biomass

Gasification involves the breakdown of large and heavy molecules of solid or liquid hydrocarbons into simpler and lighter ones. The process comprises a number of steps as shown in Fig. 5.1.

The process of gasification generally follows the following sequential steps:

- Pre-heating and drying;
- Pyrolysis;
- Char gasification and char oxidation.

Though these steps are frequently modeled in series but there is no sharp boundary dividing the steps and they often overlap. When the gasifying agent oxygen comes directly from air, the process is called "air-gasification", which produces a lower quality gas in terms of the heating value (LHV ~ 4–7 MJ/Nm^3), which issuitable for a boiler, engine and turbine operation.

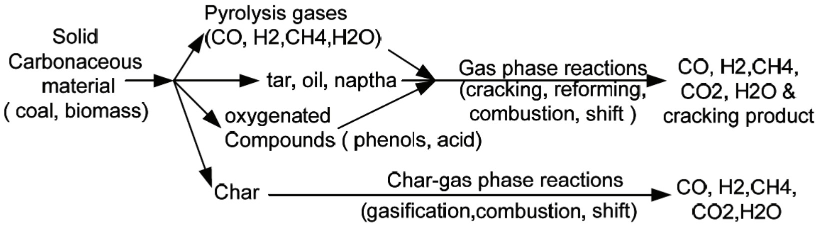


Fig. 5.1. Gasification of coal or biomass [1, 2]

It is called "oxygen or steam gasification" where the gasification medium is pure oxygen or steam respectively.

Such gasification produces a relatively high quality gas (LHV ~ 10 to 18 MJ/Nm^3) without nitrogen, and, as such, is suitable for use as synthesis gas for conversion to methanol and gasoline [3, 4].

Figure 5.2 shows conversion paths for the formation of different gasification products in C–H–O ternary diagram. If oxygen is used as a gasifying agent the conversion path points towards the oxygen corner. This path leads to a lowering of the hydrogen content and an increase in the carbon based compounds (i.e. CO and CO_2). If steam is used instead, the path points toward an increase in hydrogen.

Typical char-gasification reactions involve chemical reaction between carbon, carbon monoxide, carbon dioxide, hydrogen, water and methane. A large number of overall and intermediate reactions take place during gasification. Table 5.1 lists some of the important gasification reactions. Following two reactions with oxygen, which occur in most gasifiers, provide the necessary heat for endothermic gasification reactions.

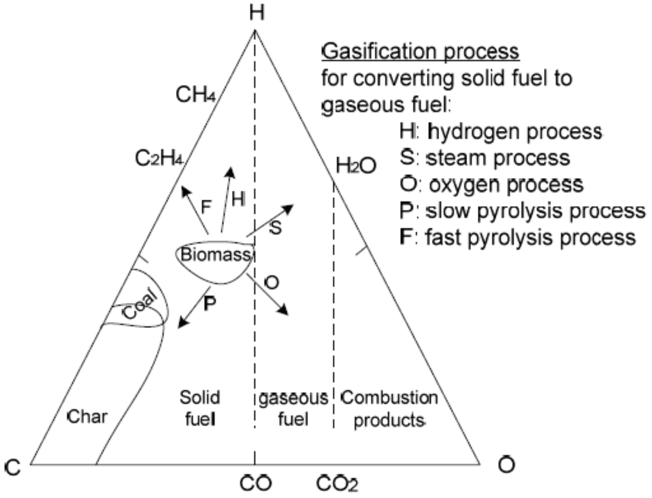


Fig. 5.2. C–H–O diagram of gasification process [2]

$$C + O_2 = CO_2 - 394 \text{ kJ/mol} \tag{5.5}$$

$$CO + 0.5\ O_2 = CO_2 -284 \text{ kJ/mol} \tag{5.6}$$

In the case of innovative gasification with steam, at the presence of calcium oxide, the heat is generated in carbonation reaction i.e. $CaO + CO_2 = CaCO_3$; simultaneously calcium cause the enhance the reaction of gasification to hydrogen.

Table 5.1. Typical gasification reactions

Reaction name	Carbon gasification		
Boudouard	R1	$C - CO_2 = 2CO + 172$ kJ/mol	a
Steam gasification/ Water–gas	R2	$C + H_2O = Co + H_2 + 131$ kJ/mol	b
Methanation	R3	$C + 2H_2 = CH_4 - 75$ kJ/mol	b
	R4	$C + 1/2O_2 = CO - 111$ kJ/mol	a
Shift reaction			
Shift	R5	$CO + H_2O = CO_2\ H_2 - 41$ kJ/mol	d
Methanation reaction			
	R6	$2CO + 2H_2 = CH_4 + CO_2 - 247$ kJ/mol	d
	R7	$CO + 3H_2 = CH_4 + H_2O - 206$ kJ/mol	d
Reforming reactions			
Steam reforming	R8	$CH_4 + H_2O = CO + 3H_2 + 206$ kJ/mol	c
	R9	$CH_4 + 0.5O_2 = CO + 2H_2 - 36$ kJ/mol	c
	R10	$CO_2 + 4H_2 = CH_4 + 2H_2O - 165$ kJ/mol	b

Table 5.1 shows how oxygen, carbon dioxide and steam – the gasifying agents react with solid carbon to convert it into low molecular weight gases like, CO, H_2.

These reactions could be either exothermic (–Q) or endothermic (+Q). For example, reactions of carbon with oxygen and hydrogen are exothermic, whereas those with CO_2 and steam are important for hydrogen production.

The final gas from gasification of solid fuel depends on the temperature and pressure of gasification process.

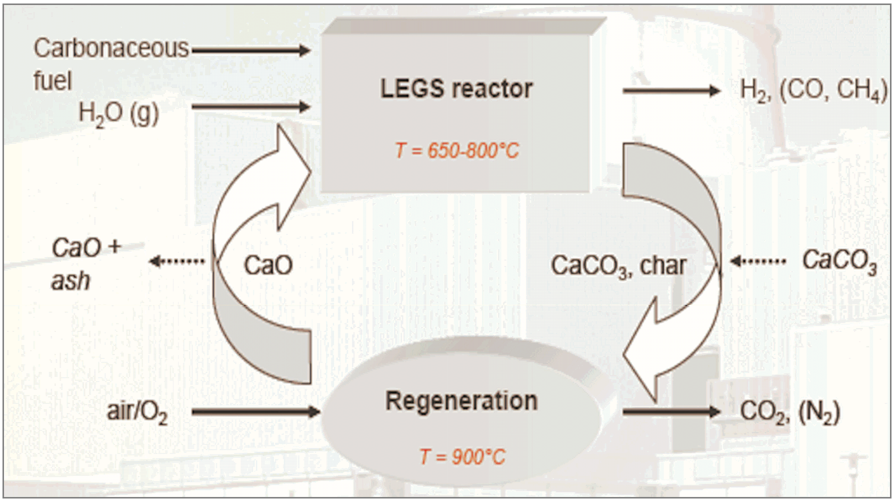


Fig. 5.3a. Scheme of ISCC process of gasification

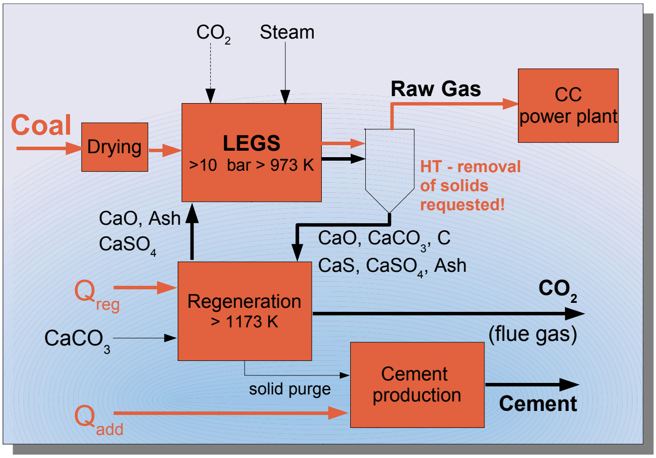


Fig. 5.3b. Scheme of modified ISCC gasification process with regeneration of calcium sorbent

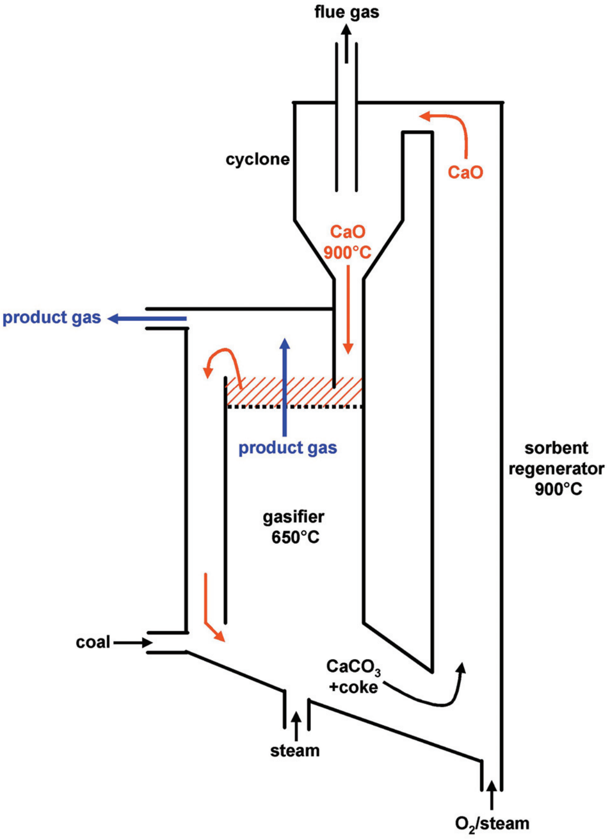


Fig. 5.3c. Technical concept of LEGS reactor for gasification with sorbent regeneration

The technology of gasification with calcium sorbent is a new method to obtain hydrogen. This technology called ISCC – *in situ* coal gasification with the CO_2 capture by calcium sorbent coupled with a regeneration unit – fig. 5.3a becomes comparable with IGCC, in the case of spent sorbent use to cement production, which is shown in fig. 5.3b. In the next figure – 5.3c – a possible technical solution is presented.

Lime Enhanced Gasification Sorbent – LEGS process produces hydrogen, the simplified LEGS reaction equation can be described as

$$\text{Fuel} + a\text{CaO} + b\text{H}_2\text{O} = x\text{H}_2 + (a–z)\ \text{CaCO}_3 + y\text{C} + z\text{CaS} \tag{5.7}$$

The above equation adds the main reactions of steam reforming – water gas shift reaction and CO_2 absorption.

Due to the strongly exothermic CO_2 absorption during steam reforming a slightly exothermic gasification reaction can be adjusted, leading to minimized energetic losses and a simple reactor design.

Beside the hydrogen rich gas a solid product consisting of limestone, CaO, char, ash, gypsum and CaS is produced during the LEGS reaction. The solid product has to be separated from the gas and must be processed in a further process unit. This process can be described as a modified lime kiln with high temperature input and simultaneous CaS oxidation.

$$(a\text{–}z)CaCO_3 + yC + zCaS + cO_2 + \text{heat} = (a\text{–}z)CaO + zCaSO_4 + ?\ CO_2 + ?\ H_2O \quad (5.8)$$

One additional advantage of the process is that the remaining char from the gasification can supply a part of the heat demand of regeneration. Regarding the equations (5.1) and (5.2) it is clear that a purge of solids is required to remove the gypsum from the system. Furthermore, this purge is required for ash removal as well.

Apart from the two main processes, the pre-treatment of fuel and the gas cleaning have two be considered as well.

Fuel

In general, suitable fuel inputs for the LEGS gasification process can be characterised as follows:

- Carbonaceous energy carriers to enable the exothermic CO_2 – absorption.
- Solid or liquid leading to upgrading to an easy combustible and clean gas.
- Humidity in the fuel may decrease steam addition.
- Ashes are suitable cement feedstock.

Based on these qualities, lignite and other low C coals seem to be perfect LEGS inputs.

Sorbent

The ideal sorbent for the LEGS process would be one fulfilling the following conditions:

- Able to react with CO_2 at sufficiently high temperatures to allow high gasification yields (*in situ*).
- High capture capacity of CO_2 (kg of CO_2/kg of sorbent).
- Low heats requirements for regeneration (low calcination heat and low fraction of inactive mass).
- Good cycle stability in many sorption-desorption cycles and/or low cost.

Natural limestones (or their derived CaO as CO_2 sorbent) fulfill very clearly the first condition.

Furthermore, the ideal capture capacity of CO_2 of a particle CaO is 78.6 w%. This means that even when molar carbonation conversions are as low as, for example 10%, the capture capacity of particles of CaO is still comparable to some synthetic sorbent being proposed for adsorption systems [3].

5.3. Hydrogen extracted from water

Hydrogen can be extracted from water:

- via biological production in an algae bioreactor,
- using electricity (by electrolysis, fig. 5.4),
- chemicals (by chemical reduction),
- heat (by thermolysis).

These methods are less developed for bulk generation in comparison to chemical paths derived.

Electrolysis of water is the decomposition of water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) due to an electric current being passed through the water. This electrolytic process is rarely used in industrial applications since hydrogen can be produced more affordably from fossil fuels

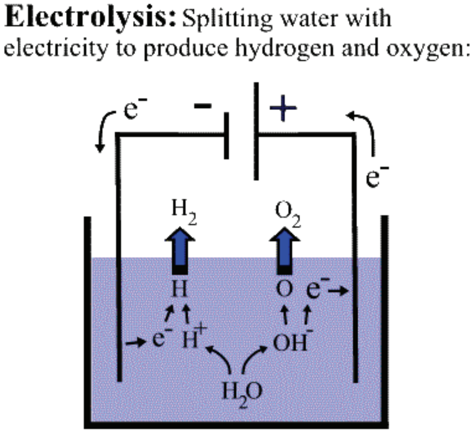


Fig. 5.4. Electrolysis

The chemical equation for electrolysis is:

$$\text{energy (electricity)} + 2\,H_2O \rightarrow O_2 + 2H_2 \tag{5.9}$$

Currently there are two methods to extract hydrogen by electrolysis:

- high pressure electrolysis,
- high temperature electrolysis.

High pressure electrolysis (HPE) is the electrolysis of water by decomposition of water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) due to an electric current being passed through the water (fig. 5.5). The difference with a standard proton exchange membrane electrolyzer is the compressed hydrogen output around 120–200 bar

(1740–2900 psi) at 70 °C. By pressurizing the hydrogen in the electrolyser the need for an external hydrogen compressor is eliminated. The average energy consumption for internal differential pressure compression is around 3%.

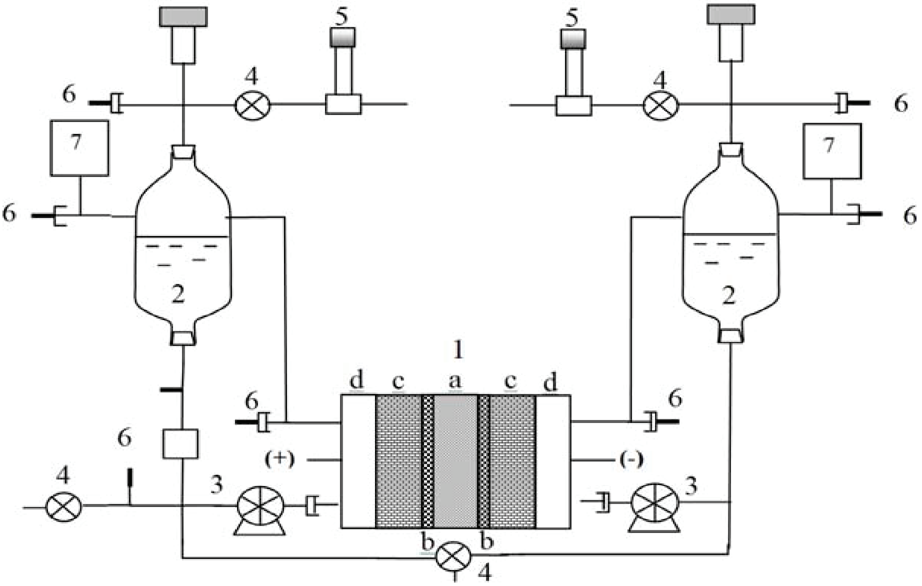
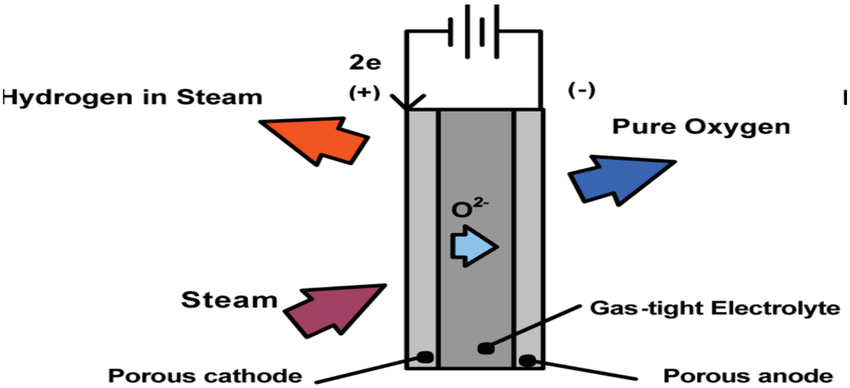


Fig. 5.5. Schematic diagram of the experimental setup:
(1-b) catalytic layers; (1-c) porous titanium current collectors;
(1-d) gas collection compartments.
Ancillary equipment: (2) liquid-gas separators; (3) pumps; (4) valves;
(5) production valves; (6) thermocouples; (7) pressure transducers.

When the energy supply is in the form of heat (solar thermal, or nuclear), the best path to hydrogen is through high-temperature electrolysis (HTE). In contrast with low-temperature electrolysis, HTE of water converts more of the initial heat energy into chemical energy (hydrogen), potentially doubling efficiency to about 50%. Because some of the energy in HTE is supplied in the form of heat, less of the energy must be converted twice (from heat to electricity, and then to chemical form), and so less energy is lost.

HTE processes are generally only considered in combination with a nuclear heat source, because the other non-chemical form of high-temperature heat (concentrating solar thermal) is not consistent enough to bring down the capital costs of the HTE equipment. Research into HTE and high-temperature nuclear reactors may eventually lead to a hydrogen supply that is cost-competitive with natural gas steam reforming. HTE has been demonstrated in a laboratory, but not at a commercial scale. The scheme of that system in is shown in fig. 5.6.



High Temperature Electrolysis using a Nuclear Reactor Heat Source

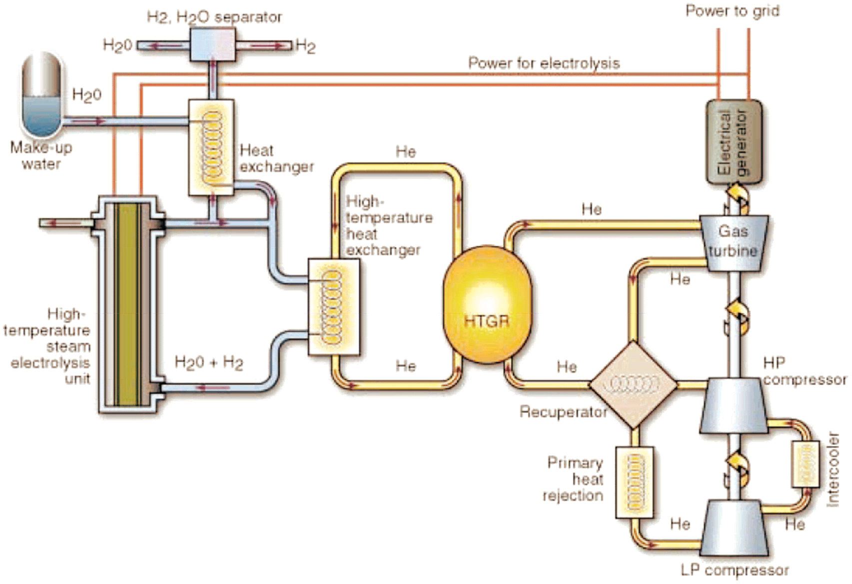


Fig. 5.6. The scheme of hydrogen production system

Hydrogen can also be produced through a direct chemical path using electrolysis. With a renewable electrical energy supply, such as hydropower, wind turbines, or photovoltaic cells, electrolysis of water allows hydrogen to be made from water without pollution. Usually, the electricity consumed is more valuable than the hydrogen produced, so this method was not widely used in the past, but the importance of high pressure electrolysis is increasing as human population and pollution increase, and electrolysis will become more economically competitive as non-renewable resources (carbon compounds) dwindle and governments remove subsidies on carbon-based fuels.

Direct Hydrogen Production

Direct water-splitting technologies – using photo electrochemical devices or photosynthetic microorganisms – are the "Holy Grail" of the hydrogen economy (fig. 5.7). These processes use energy from sunlight to dissociate water into hydrogen and oxygen. They are the ultimate clean and sustainable hydrogen production methods. Although, not ready for prime time, photo electrochemical and photo biological technologies show great promise for the future, and are the focus of long-term research and development at many laboratories.

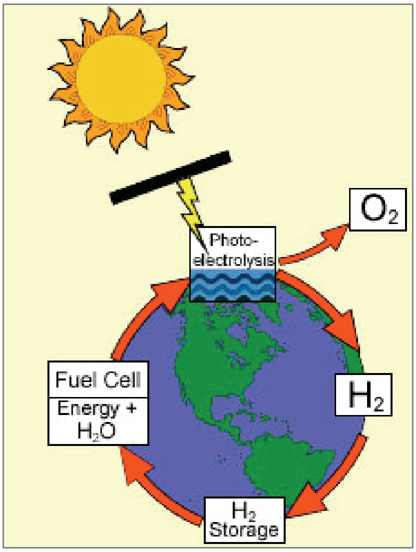


Fig. 5.7. The hydrogen cycle: when generated from renewable sources, such as via photoelectrolysis, hydrogen production and use are part of a clean, cyclic process

Photoelectrochemical method of hydrogen production

A photo-electro-chemical (PEC) hydrogen system integrates photovoltaic (PV) material with an electrolyzer to produce hydrogen directly from water, using only sunlight.

This system offers many benefits over two-step processes in which the PV cells and electrolyzer are separate components of the system. Combining the two components in a single PEC device can eliminate most of the electrolyzer costs and reduce semiconductor processing because surface contacts, interconnects, and wiring are no longer necessary. It can also increase the efficiency of the process by 30%, the further reduction of the cost of delivered hydrogen. The basic PEC hydrogen production system consists of two electrodes – a semiconductor electrode and a platinum metal electrode – immersed in an aqueous electrolyte. But instead of using electricity from an external source like wind power, the semiconductor absorbs light energy and generates the electrical current that drives the electrolysis reaction, splitting water into hydrogen at the semiconductor surface, and oxygen at the metal electrode surface. Although simple in concept, the challenge is to find a material that can drive this one-step process. For it to be viable, two criteria must be met – the light-harvesting system must have the correct energy to drive the electrolysis, and the system must be stable in an aqueous environment. So far, no single semiconductor that satisfies all of the criteria to be used in a hydrogen-evolving PEC system has been identified. The most stable semiconductors in aqueous solution are oxides, but their band gaps are too large for efficient light absorption, or their semiconductor characteristics are poor. Semiconductors with better solid-state characteristics are typically thermo- dynamically unstable with respect to oxidation. Finding a material that can drive the process is the key to the success of PEC hydrogen production. Materials now under evaluation – gallium nitrides, amorphous silicon, and copper indium gallium diselenide films (CIGS) – build on materials developed for PV. A variety of surface treatments – protective coatings and band-edge engineering – are also being evaluated to address energetic issues, corrosion problems, and catalysts for the water-splitting reactions.

In a PEC hydrogen system (fig. 5.8), a semiconductor cell and a platinum metal electrode are immersed in an aqueous electrolyte. The semiconductor absorbs light energy to generate the current that drives the electrolytic reaction, with hydrogen produced at the semiconductor electrode and oxygen at the metal electrode.

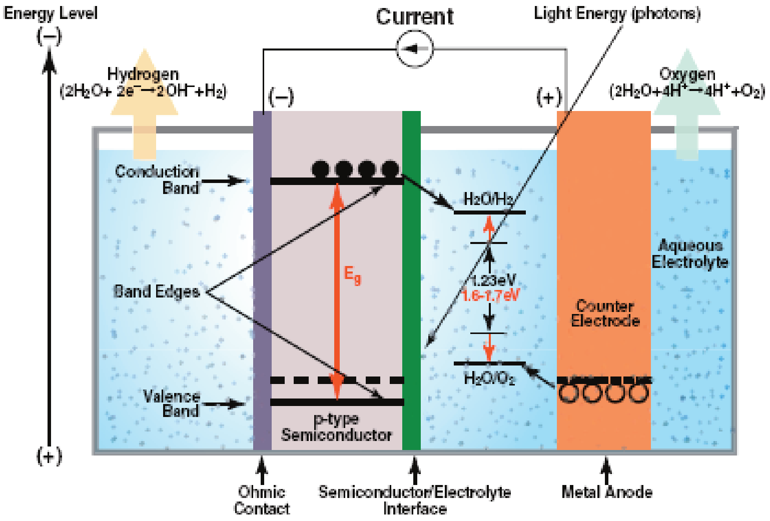


Fig. 5.8. PEC hydrogen system

For this configuration to enable work, the band gap of the semiconductor must be between 1.6 eV and 2.2 eV, the band edges must straddle the water redox potential, the system must be stable in solution, and the charge must be transferred quickly from the semiconductor surface to the water.

Gallium nitrides, although expensive, are good candidates for PEC hydrogen systems because they show high efficiencies, are chemically stable, and their band gaps can be adjusted by altering their composition to produce alloys of gallium nitride. Gallium phosphide nitride and indium gallium nitride are being evaluated to determine if they can be tailored to meet the requirements for solar water-splitting. Amorphous silicon (a-Si) multijunction systems developed for PV offer a lower-cost alternative to gallium nitride materials. Triple-junction a-Si devices have voltages sufficient for water splitting, and the cells can be tailored to produce voltages matched to the energetic requirements of water splitting, maximizing overall efficiency. But a-Si is unstable in aqueous solutions and must be protected by a corrosion-resistant coating in a PEC-hydrogen system. To maintain the function of the semiconductor, the coating material must be stable, transparent, and conductive. For this, researchers are evaluating silicon nitride compositions. Semiconductor materials based on polycrystal-line thin films, such as CIGS, are also promising alternatives. They are made with inexpensive techniques and can reach efficiencies greater than 15%, both of which help reduce costs.

Incorporating sulfur into CIGS increases the band gap into the range required for PEC water-splitting. Designing a viable CIGS water splitting device would greatly decrease PEC hydrogen production costs. Once we identify a semiconductor material with the ideal band gap and chemical stability, it still won’t split water unless the semiconductor band edges overlap the water redox potential. This energetic mismatch can be overcome by using a tandem semiconductor system or by modifying the semiconductor band edges. NREL researchers [6] have demonstrated a solar-to-hydrogen conversion efficiency of 12.4% using a unique structure based on a gallium indium phosphide/gallium arsenide (GaInP2/GaAs) tandem system. In this configuration, the GaAs cell generates the additional voltage needed to overcome energating the effects of adsorption of organometalic compounds on the band-edge properties of GaInP2. In theory, these materials should shift the band edges into the water-splitting range, and speed up the charge transfer rate at the surface. Understanding and controlling the interfacial properties of semiconductor electrodes is the key to successful production of hydrogen from PEC systems. The development and characterization of new semiconducting materials and systems are critical for the future viability of PEC-driven hydro-generation. Continuation of the collaborative relationship between PV and PEC hydrogen R&D will accelerate progress in identifying and synthesizing more efficient, lower-cost, and electrochemically stable, solid-state materials and systems.

Photobiological research

The green algae, *Chlamydomonas reinhardtii*, is one of several microorganisms that use sunlight to produce hydrogen directly from water. Like all green plants, these green algae also produce oxygen during photosynthesis.

Photosynthetic green algae and cyanobacteria provide a more promising pathway for generating hydrogen on a large scale. Hydrogen production by these microorganisms depends on the availability of plentiful resources, namely water as a substrate and solar energy as the energy source. Moreover, the oxygen and hydrogen that such cells produce could be used in a fuel cell to generate electricity (fig. 5.9).

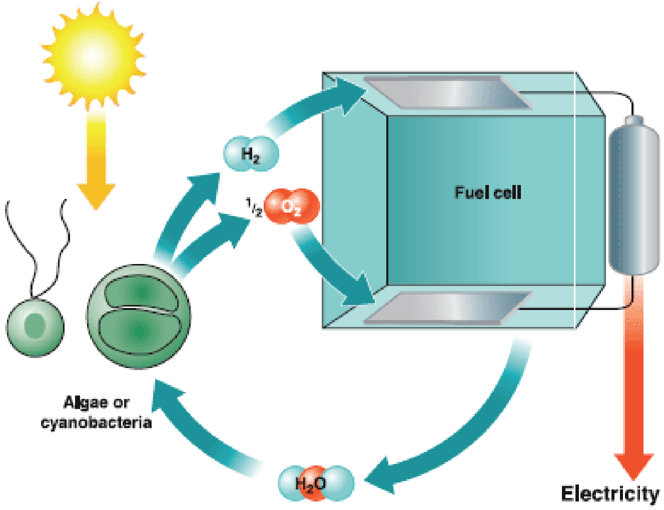


Fig. 5.9. Illustration of photo-biological H_2 production and its utilization in a H_2 fuel cell

Unfortunately, oxygen inhibits the function of algal hydrogenise, the enzyme in Chlamydomonas that catalyzes the release of hydrogen gas. So, under normal conditions, i.e., in sunlight, the alga cannot sustain hydrogen production for more than a few minutes. Before photobiological hydrogen production can become a viable commercial-scale option, scientists need to find ways to control the oxygen sensitivity of the hydrogenase. Researchers are attacking this problem on two fronts – by isolating new forms of the organism that can sustain hydrogen production in the presence of oxygen and by developing processes that separate the oxygen and hydrogen production reactions in the algae. In the first approach, researchers are using advanced molecular engineering to design hydrogenase enzymes that are more resistant to oxygen inactivation. Past research indicates that the oxygen inactivation occurs when oxygen binds directly with one of the iron species located at the catalytic center of the enzyme. Researchers developed a model of the hydrogenase structure to help identify regions in the enzyme most likely to be involved in the oxygen access to the catalytic site. This

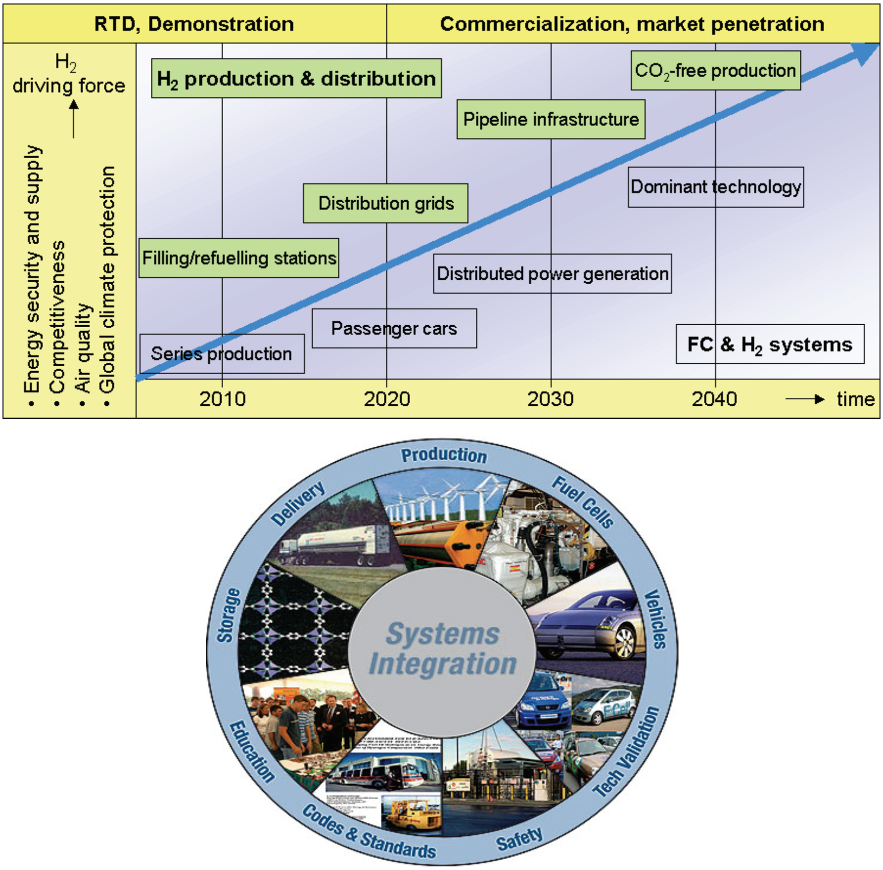


Fig. 5.10. Elements of the Hydrogen Economy

led to the discovery that the gas channel, which allows hydrogen to diffuse out of the catalytic center of the enzyme, is large enough to allow oxygen to flow back into the catalytic site and deactivate the enzyme. Researchers inserted bulky amino acid molecules along the gas channel walls to reduce the size of the channel so that hydrogen, but not oxygen, could flow through it. This modified enzyme appears more resistant to oxygen deactivation than the original. Researchers are continuing this molecular engineering approach to the further improvement of the oxygen tolerance of the alga. In the second approach, researchers are identifying and characterizing the process conditions that allow the algae to produce either oxygen or hydrogen, but not both simultaneously. They designed a metabolic switch to create a cycle of algal cells between a photosynthetic growth phase, which produces oxygen, and a hydrogen production phase. The switch is based on withholding sulfur, essential for maintaining normal photosynthesis; without it, the algae decrease their photosynthetic activities to low levels (such that any oxygen evolved is immediately consumed by the respiratory activity of the culture) and become anaerobic in the light. As a consequence, they switch to a different metabolic pathway – the one that utilizes the reductants generated by water oxidation to produce hydrogen gas instead.

The cost effective hydrogen production technology should be solved, but, additionally, the hydrogen management is the second critical point. And that needs a solution. Then the hydrogen will be competitive with conventional fuels (fig. 5.10).

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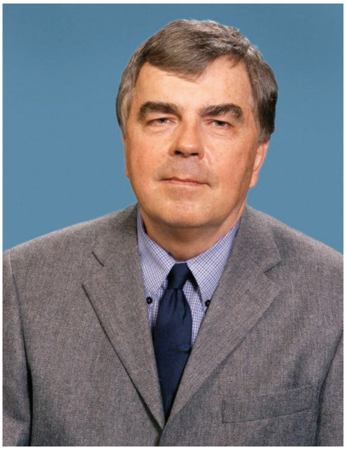

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In this book the five chapters cov
renewable energy problems such as:
and renewable energy power systems, some problems of the conversion of the solar radiation to the heat and to the electricity, thermodynamics of biomass gasification, technical problems associated with the biomass gasification and hydrogen as a future fuel. This book is for researches and for anyone who deals with conventional and renewable energy systems.

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