Solarthermal Power Plant (STPP) Technology

TEMO-STPP Test Stand 1: Fluid Flow, Heat Transfer and combustion regulation at heater-absorption pipe system

Last update: 26 December 2010

Fig.1: Principle of hybrid test stand

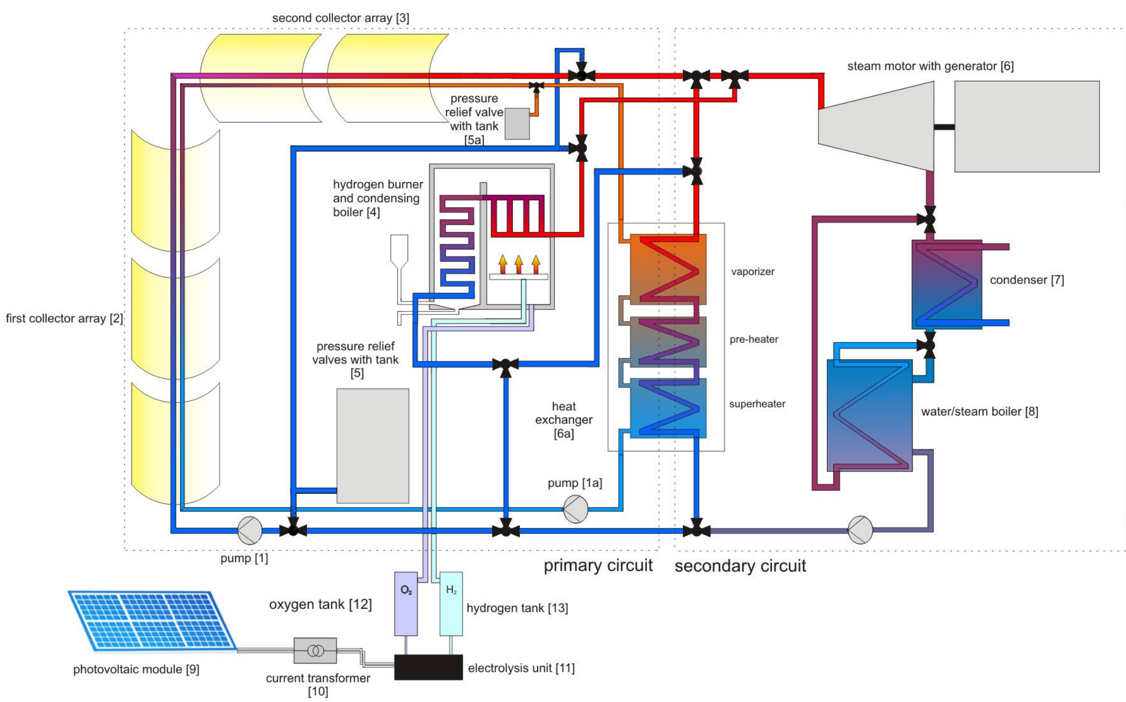
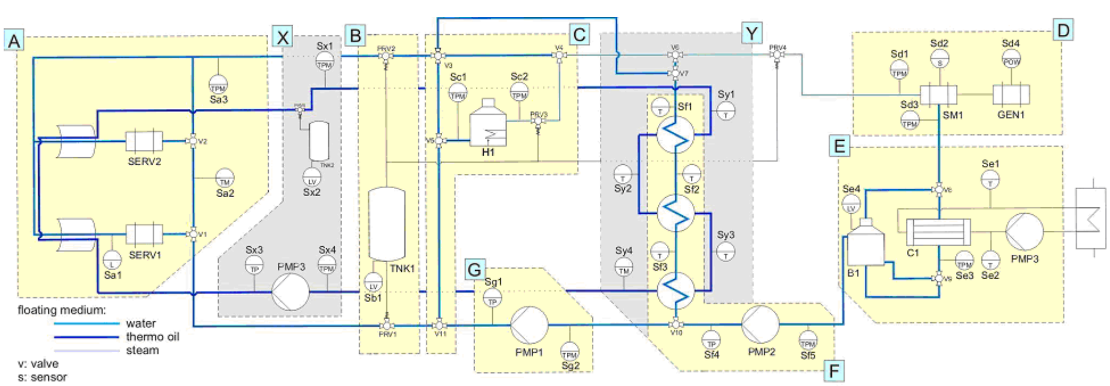


Fig.2: Process Control System (System Architecture)



Architecture of process control system (sensors and actuators)

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Fig. 3: Absorption Pipe

The absorption pipe is one of the basic essentials of the system. Here, the thermal energy of the sun's rays is absorbed to be transmitted to the water/thermo oil. The absorption pipe is exactly located in the focal point of the parabolic mirrors, which are reflecting the sun. So the sun's rays are concentrated on the absorption pipe. Temperatures about 400°C are reached on the pipe's surface. That allows the heating of the water/thermo oil at least up to, which are required to run the steam engine.

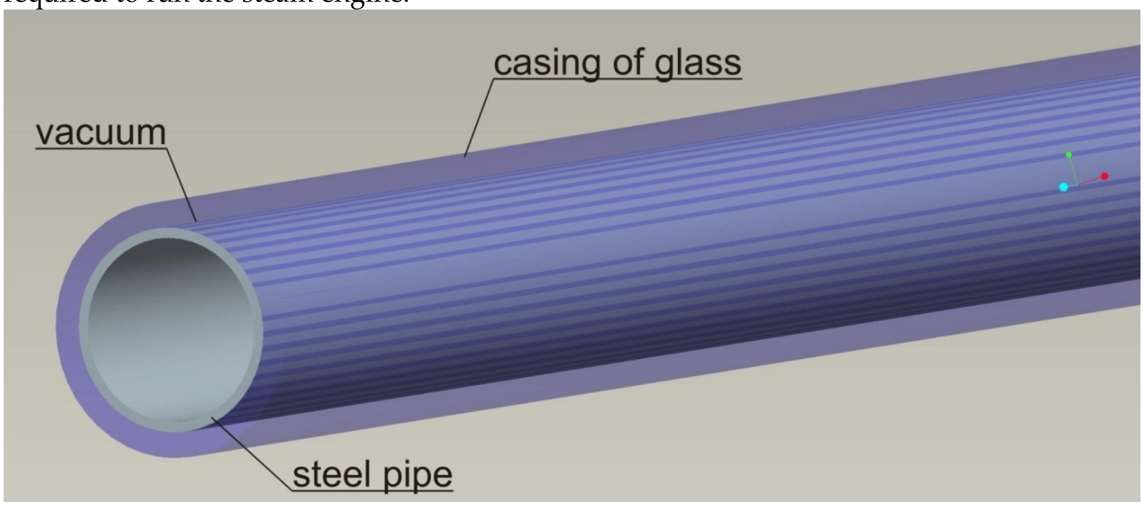


Figure: Sketch of the absorption pipe

The particular with the absorption pipe is a layer of vacuum inside. The active principle is the same as it is used for thermos bottles or double layer window pane. The absorption pipe consists of two interleaved pipes with this layer of vacuum inside to isolate thermal one pipe from the other.

In the ideal case vacuum is an absolute empty space. For thermal conduction in a space, at least the existence of atoms or gas molecules is necessary. So, there is no possibility for thermal conduction. For convective heat transfer any kind of stream is required. In vacuum stream does not take place because there is no material that could flow. So, there is also no possibility for convective heat transfer.

There is only heat radiation as a form of thermal transfer taking place in vacuum. The sun emits very strong heat radiation, which is amplified over again by concentrating the sun's rays by the parabolic mirrors. The high energy radiation shines through the external pipe, made of a special kind of glass, which has the same thermal expansion as steel has, to avoid tensions in the pipe. So the heat radiation gets to the internal pipe and heats up its surface. Through thermal conduction the heat is delivered to the fluid circulating in the pipe.

The effect of thermal conduction through the pipe can be increased by using special alloys. The vacuum around the internal pipe causes that the heat energy is not emitted to the environment but directly conducted in the pipe. The heated up pipes themselves also loose heat energy by heat radiation. But the intensity of this heat loss is, compared to heat of the concentrated sun rays, insignificant minor.
The absorption pipes will be delivered by an Austrian company. The diameter of these pipes is varying because of the pipes are to be optimized by being used in this project. That also effects advantages for the project and is welcome by the management of the TEMO STPP.

Fig. 4: The Collector

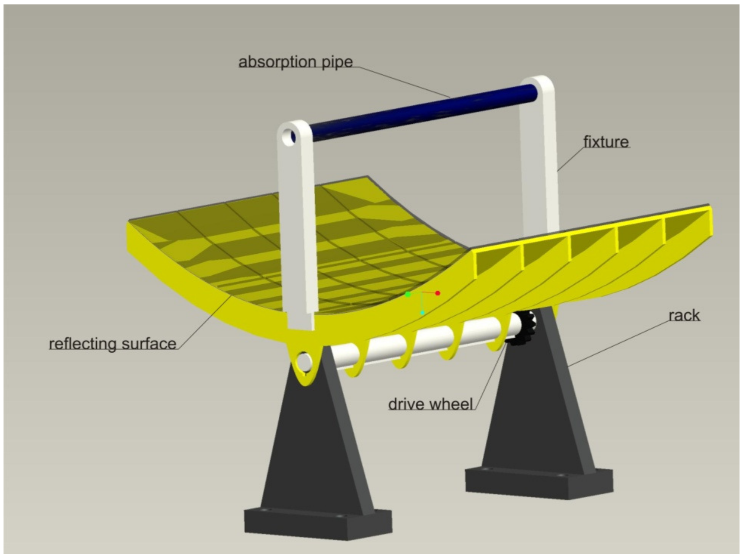


Figure: ProE model of the collector

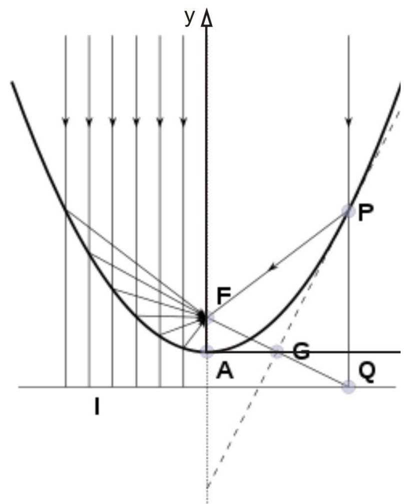


Figure: **Focal point F of a parabola**

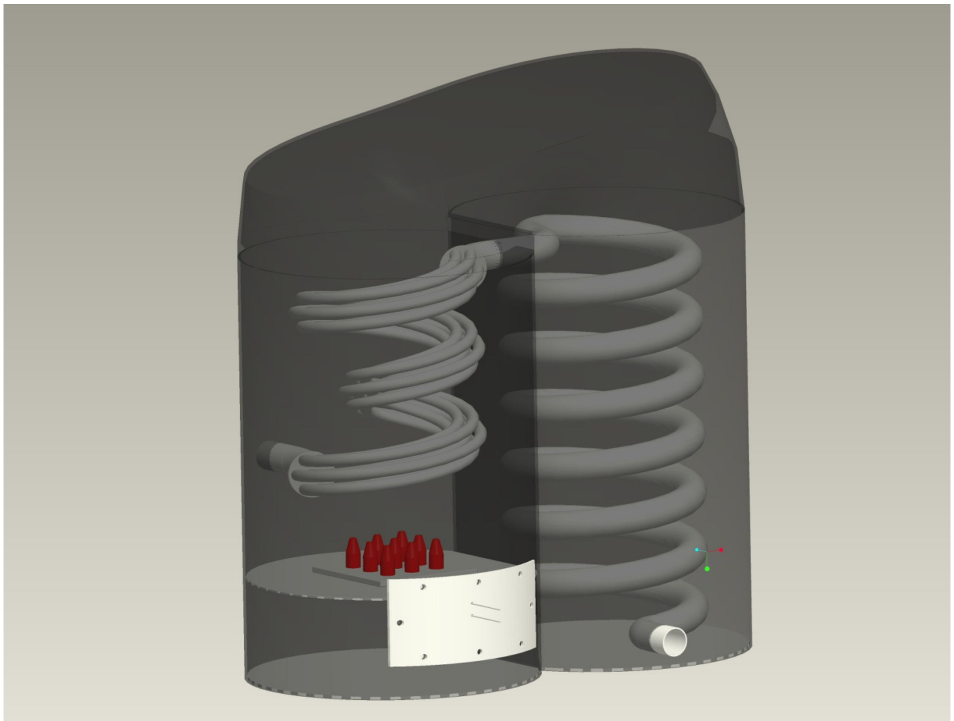
Following scale shows the design data of the parabolic mirrors.

total span width	x_{max}	$5m$
total height	y_{max}	$0{,}88m$
Parabola	$y = 0{,}1408\ \frac{1}{m} * x^2$	
focal point height	f	$1{,}96m$

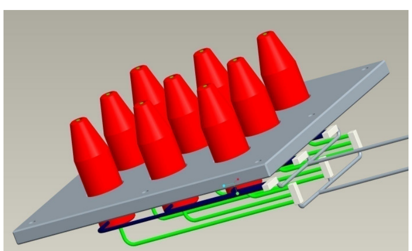
Table: design data of the parabolic mirrors

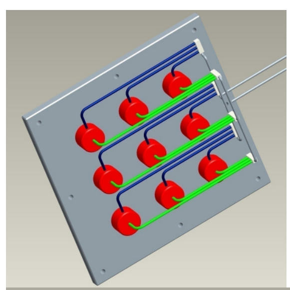
Fig. 5: The Heater

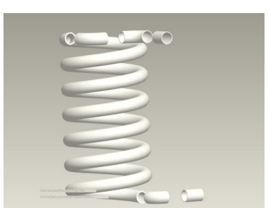
a mixture of 50 percentages hydrogen, domestic gas and 20-30 percentages methane as a catalyst (was in use in the newly-formed German states until 1996, known as “Stadtgas)

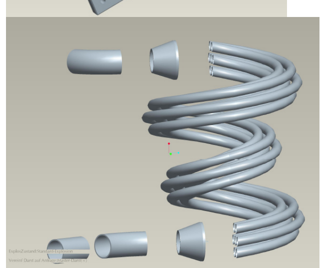


Hydrogen burner and condensing boiler









Exact calculations of the combusting process of hydrogen and oxygen have to be done. Computational Fluid Dynamics (CFD) software, which allows displaying combusting processes, has to be used to gain in experience in the air currents.
For instance, such software is ANSYS. [http://www.ansys.com] or ABAQUS

Heater and Combustion Problem

The idea of combusting hydrogen to superheat the steam in the test stage and to drive the rig at bad solar conditions and at night in the operating stage is ambivalent. On the one hand this idea promises total independence of fossil fuels. Otherwise it is an unproved technology. The emerging oxyhydrogen is a high potential danger because of its explosive characteristic. A compromise proposal is to combust a mixture of hydrogen and domestic gas. Tests made by Stadtwerke Bonn in 2000 with a ratio up to 50 percentages of hydrogen succeeded [http://www.solarhydrogen.com]. The used heaters were light modified conventional condensing boilers. Furthermore, a mixture of 50 percentages hydrogen, domestic gas and 20-30 percentages methane as a catalyst was in use in the newly-formed German states until 1996, known under the name “Stadtgas”.

Heat transmission in the condensing boiler

The enthalpy of the water at the conditions before entering the condensing boiler (100 to 110°C, 11 bar) is H_{water} = $419.849 - 462.059 \frac{kJ}{kg}$.
The enthalpy of the steam at the conditions after leaving the condensing boiler (200 °C, 11 bar) is H_{steam} = $2822{,}261 \frac{kJ}{kg}$.

The enthalpy of evaporation at the point of saturation (184°C,11bar) is $\triangle H_{vaporization}$= $2014 \frac{kJ}{kg}$.
To calculate the enthalpy total spent, the difference between before and after the condensing boiler is to build. Then, added the enthalpy of evaporation, the result is the total used up enthalpy H_{tot} = $4374{,}202 - 4416{,}412 \frac{kJ}{kg}$.
The values’ source is the software THexcel, a Microsoft Excel Application for calculation in thermodynamics by Ing. Büro für Energietechnik und Software, 51469 Bergisch Gladbach, Germany. [http://www.thexcel.de]

Burning process of hydrogen

The combusting of hydrogen is an exothermal reaction. The elemental formula is

$$2\,H_2 \;+\; O_2 \;\rightarrow 2\,H_2O \qquad (2.13)$$

$$2 \cdot 0 \;+\; 1 \cdot 0 \;\rightarrow\; 2 \cdot (-285 kJ/mole) \;=\; -572\; kJ/mole \qquad (2.14)$$

$H_2: hydrogen$

$O_2: oxygen$

$H_2O: water$

The resulting energy of this chemical reaction is $\triangle H_R$ = 572 kJ / mole. That means that you get 572 kJ per mole of synthesized water. A mole has 6.0221415×10^{23} atoms or molecules of the pure substance. The molar mass of water is

$$M_{\mathrm{H_2O}} = 2M_H + M_O = 2 \cdot 1{,}00794 \frac{g}{mol} + 15{,}9994 \frac{g}{mol}$$

= 18,01528 *g/mol* *(2.15)*

As a result the mass of $1\ mole$ of water is $18{,}01528\ grams$. Accordingly the release of energy by the synthesis of $2{,}01588\ grams$ of hydrogen and $15{,}9994\ grams$ of oxygen to $18{,}01528\ grams$ of water is 572 kJ.
The required energy to heat up isobaric the flow of water from 100 to 110 °C and $1.1\ MPa$ (=11 bar) to steam at 200 °C and $1{,}1\ MPa$ is 4374,202 to 4416,412 kJ/kg (s. Ch. 5.2.3).
The mass flow is 0,7 kg/s. So the required heating power ranges from

$$0{,}7 kg/s \cdot 4374{,}202\ kJ/kg = 3061{,}941\ kJ/s$$

$$= 3061{,}941\ kW, \tag{2.16}$$

if the inlet temperature is 100°C,
to

$$\frac{0{,}7kg}{s} \cdot 4416{,}412 \frac{kJ}{kg} = 3091{,}488 \frac{kJ}{s}$$

$$= 3091{,}488\ kW, \tag{2.17}$$

if the inlet temperature is 110°C.

The quotient of $3061{,}941 \frac{kJ}{s}$ and $572\ kJ$ is 5,352 /s, that means that it is necessary to combust at least

$$5{,}353\ /s \cdot 2{,}01588\ grams = 10{,}791 \frac{grams}{s} \text{ of hydrogen} \tag{2.18}$$

and

$$5{,}353\ /s \cdot 15{,}9994\ grams = 85{,}645 \frac{grams}{s} \text{ of oxygen.} \tag{2.19}$$

To bear in mind that the hydrogen burner and condensing boiler reaches up to 90 percentage of efficiency, the calculated values have to be multiplied by 10/9.
So the mass flow of hydrogen, which has to be combusted in the burner, is at least

$$10{,}791 \frac{grams}{s} \cdot \frac{10}{9} = 11{,}99 \text{ grams per second.} \tag{2.20}$$

The mass flow of oxygen, which has to be combusted in the burner, is at least

$$85{,}645 \frac{grams}{s} \cdot \frac{10}{9} = 95{,}16 \text{ grams per second.} \tag{2.21}$$

Heat transmission in the absorption pipes

To calculate the heat transmission in the absorption pipes the first step is to form the thermal balance:

$$J_{q,konv}(x) \cdot J_{q,\ddot{u}ber}(x) - J_{q,konv}(x + \Delta x) \tag{2.22}$$

After setting in the definitions:

$$c_p \cdot \dot{m} \cdot T(x) + k \cdot U \cdot \Delta x \cdot (T_{ma} - T(x)) = c_p \cdot \dot{m} \cdot T(x + \Delta x) \tag{2.23}$$

With:

$$T(x + \Delta x) = T(x) + \frac{dT}{dx} \cdot \Delta x + \cdots \tag{2.24}$$

The result is:

$$c_p \cdot \dot{m} \cdot T(x) + k \cdot U \cdot \Delta x \cdot (T_{ma} - T(x)) = c_p \cdot \dot{m} \cdot \left(T(x) + \frac{dT}{dx} \cdot \Delta x\right) \tag{2.25}$$

Cancelled down:

$$k \cdot U \cdot (T_{ma} - T(x)) = c_p \cdot \dot{m} \cdot \frac{dT}{dx} \tag{2.26}$$

with:

$$dT = d(T_{ma} - T(x)) \tag{2.27}$$

Separation of the variables:

$$\frac{k \cdot U}{c_p \cdot \dot{m}} dx = \frac{d(T_{ma} - T(x))}{T_{ma} - T(x)} \tag{2.28}$$

Integration:

$$\frac{k \cdot U}{c_p \cdot \dot{m}} \cdot x = -\ln[(T]_{ma} - T(x)) + C \tag{2.29}$$

Aperture (pipe shell) A_i:

$$A_i = U \cdot x \tag{2.30}$$

With boundary conditions:

$$A_i = 0, \qquad T(x) = T_0$$

The constant of integration is:

$$C = [ln(T]_{ma} - T_0) \tag{2.31}$$

Setting in the boundary conditions:

$$\frac{k \cdot U}{c_p \cdot \dot{m}} \cdot x = -\ln[(T]_{ma} - T(x)) + [ln(T]_{ma} - T_0) \tag{2.32}$$

Dissolving with respect to x:

$$T(x) = T_{ma} - (T_{ma} - T_0) \cdot e^{-(k \cdot A_i/(\dot{m} \cdot c_p)} \tag{2.33}$$

T_{ma} = temperature pipe surface exterior
T_0 = temperature of the flow by entering the absorption pipe
A_i = aperature (pipe surface exterior)
There is a logarithmical temperature profile for steady heat conduction through cylindrical geometries:
Heat conduction through the pipe wall J_q:

$$J_q = \lambda \cdot \frac{2\pi \cdot L}{\frac{\ln R_a}{R_i}} \cdot (Ti - Ta) \tag{2.34}$$

Coefficient of heat transmission k_i:

$$k_i = \frac{J_q}{A_{äqui} \cdot \Delta T} \tag{2.35}$$

Heat transmitting surface $A_{äqui}$:

$$A_{äqui} = 2\pi \cdot L \tag{2.36}$$

Setting in:

$$k_i = \lambda \cdot \frac{1}{\frac{\ln R_a}{R_i}} \tag{2.37}$$

Coefficient of heat transmission composed of heat conduction through the copper pipe and heat transmission from the copper pipe to the floating medium:

$$\frac{1}{k} = \frac{1}{\Sigma k_i} = \frac{1}{\alpha} + \frac{ln\frac{R_a}{R_i}}{\lambda_{Kupfer}} \tag{2.38}$$

Coefficient of heat transmission from the copper pipe to the floating medium α

$$\alpha = \frac{Nu \cdot \lambda}{L_{äqui}} \tag{2.39}$$

$\lambda = \; specific\ heat\ conductivity$

The Nusselt number Nu is the ratio of convective to conductive heat transfer across the boundary:

$$Nu = 0{,}3 + 0{,}037 \cdot Re^{0{,}8} \cdot Pr \cdot \left(1 + 2{,}443 \cdot \left(Pr^{\frac{2}{3}} - 1\right) \cdot Re^{-0{,}1}\right)^{-1} \tag{2.40}$$

Reynolds number Re is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.

$$Re = \frac{\rho \cdot v \cdot D}{\mu} = \frac{v \cdot D}{\nu} \tag{2.41}$$

$\rho = density\ of\ the\ floating\ medium$

$v = velocity\ of\ the\ floating\ medium$

$D = diameter\ interior\ of\ the\ pipe$

$\mu = dynamic\ viscosity\ of\ the\ floating\ medium$

$\nu = kinematic\ viscosity\ of\ the\ floating\ medium$