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Solar Water Heating Theory

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The
Objective
of this talk is to present the
basic theory
on which solar water heaters work.

We will consider
flat plate solar water heaters
(both thermosyphon and pumped)
as well as
evacuated tube solar water heaters

Contents

How do we?:

- Collect the heat
- Transport the heat
- Store the transferred heat

A little about myself

1970-1980 Nuclear Energy
1980-1985 Solar Energy
1985-1988 Missile Manufacture Management
1988-2008 Heat Transfer Lecturer

My research philosophy is:

<u>Adaptive engineering</u>
were we try and engineer our heat transfer systems to make exclusive use of
<u>natural forces</u>
such as gravity, surface tension density gradients and buoyancy
<u>to do the job for us</u>
without the use of any mechanically moving parts such as pumps and mechanical activators and active electronic and mechanical controls and switches

We used the roof and the car park as our solar water heater test laboratory at Kwikot LTD, Edinburg Road, Benoni

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Thelma (Kwikot Factory Personal manager) cooking pap along side Benoni Lake in 1983

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Front and back-page of our "Frost Resistance" Panel

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Solar water heater configurations

- Integral
- Thermosyphon
- Pumped
- Close-coupled
- Swimming pool

Integral solar water heater

Solar collector and Water Storage all in one unit

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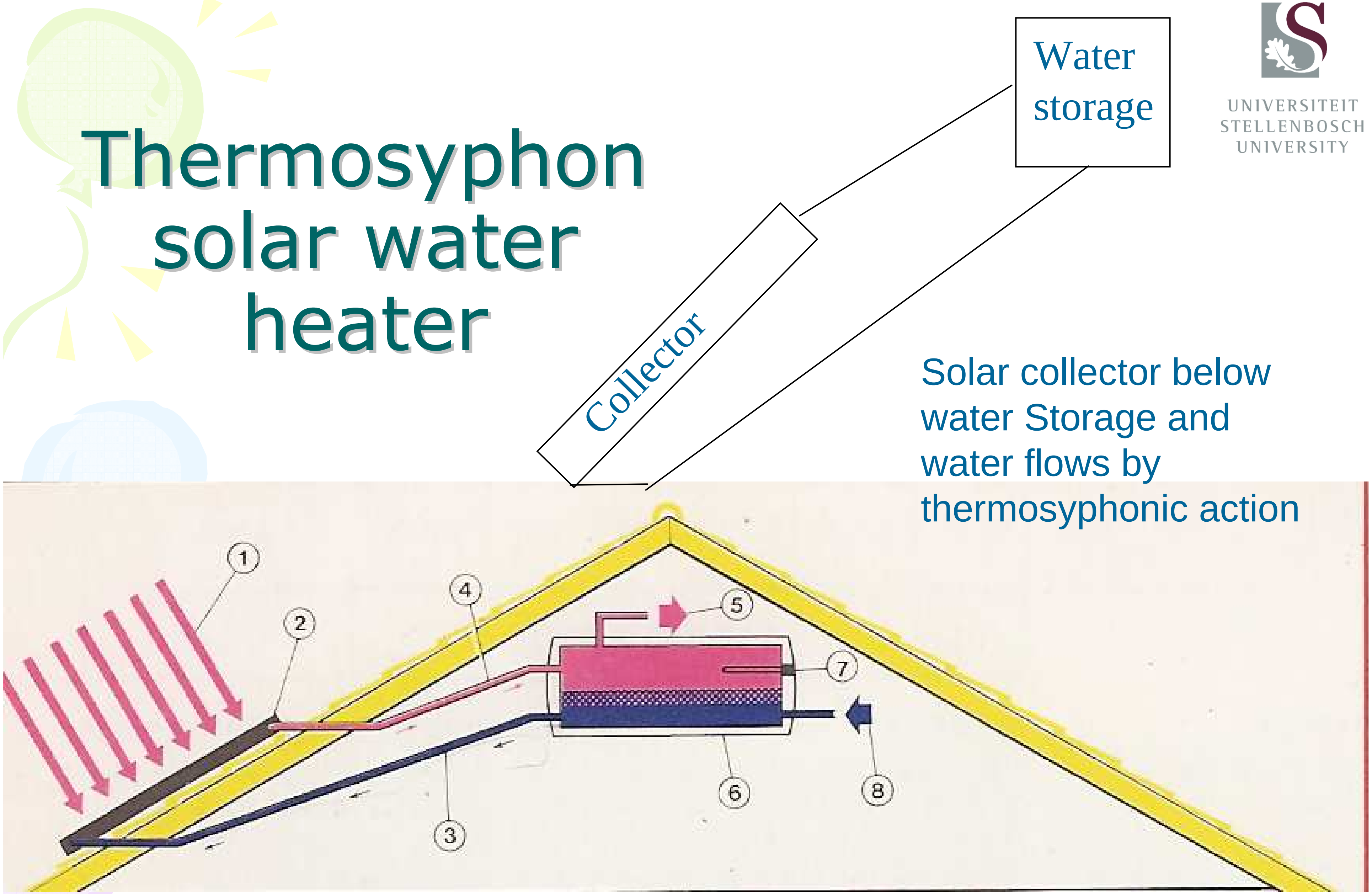
Thermosyphon solar water heater

Solar collector below water Storage and water flows by thermosyphonic action



Pumped solar water heater

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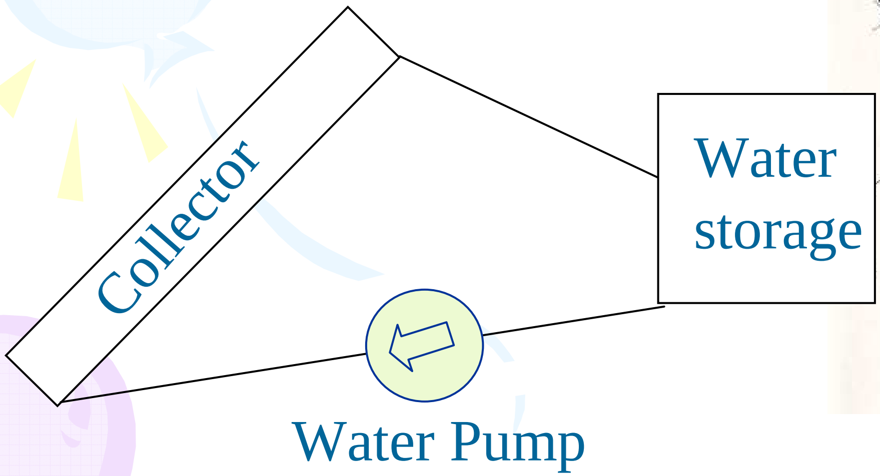
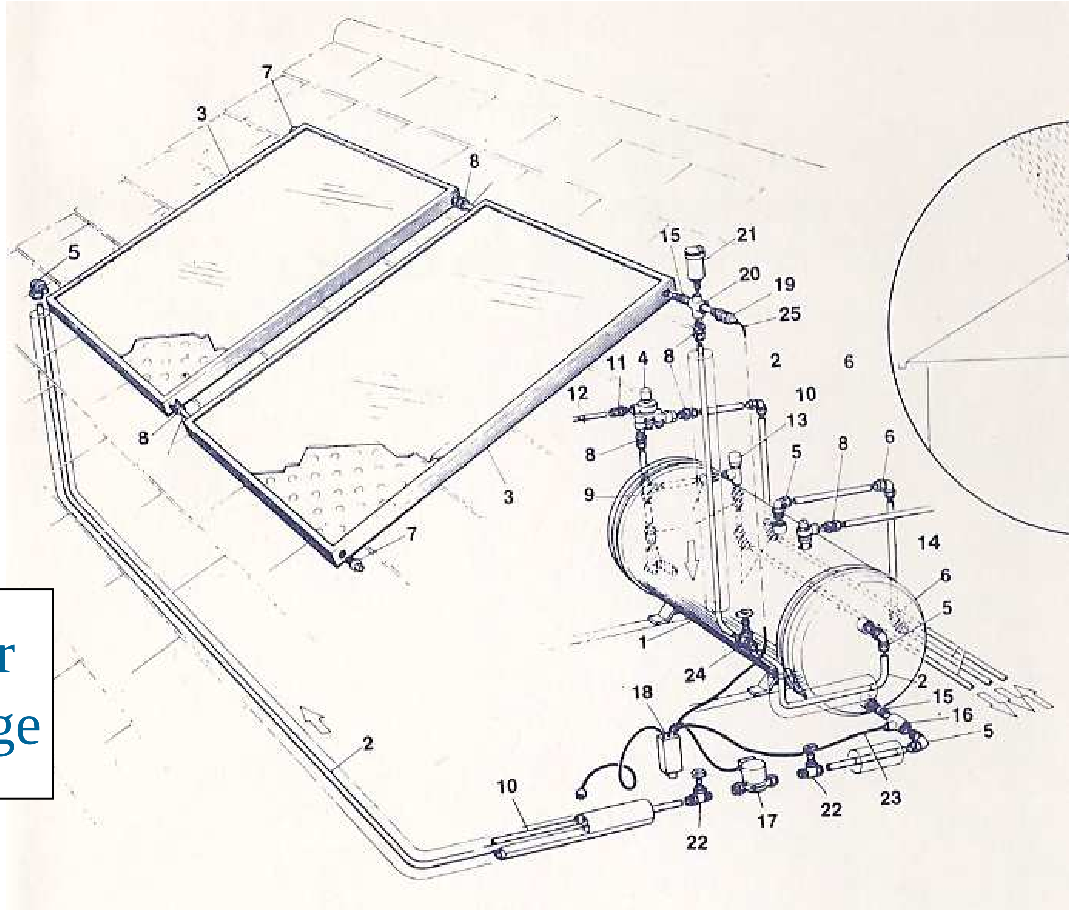
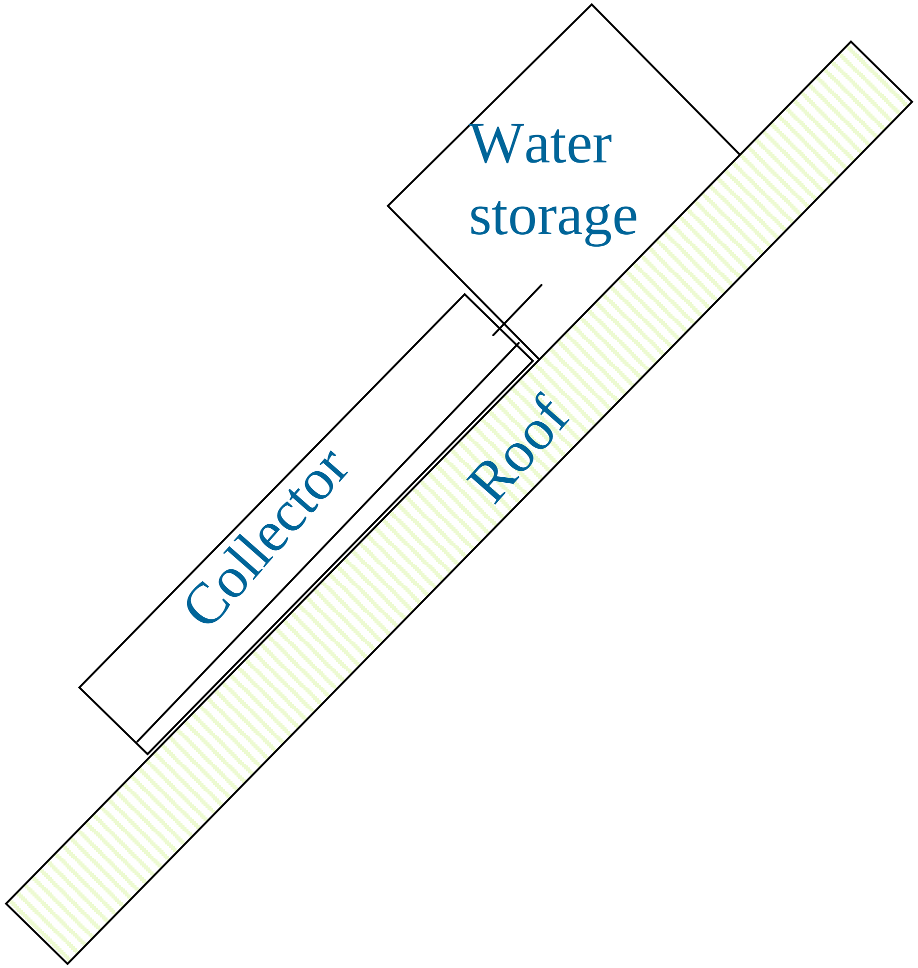
Solar collector below water storage. Water is pumped





Close-coupled Thermosypon solar water heater

Solar collector and water storage separated but on a common integrated support platform to look like a single unit



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Close-coupled Indirect Tank-in-Tank Thermosyphon solar water heater

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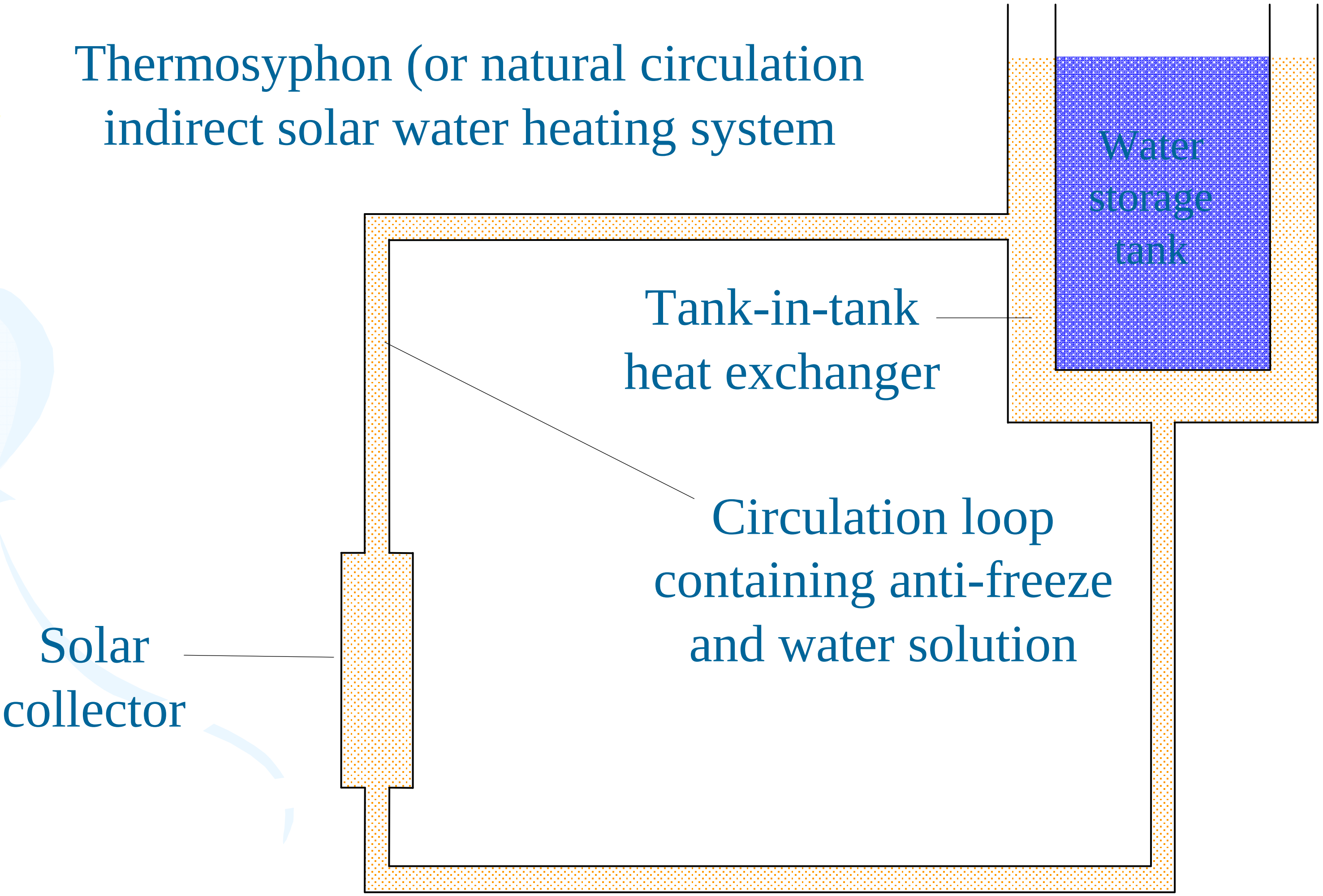
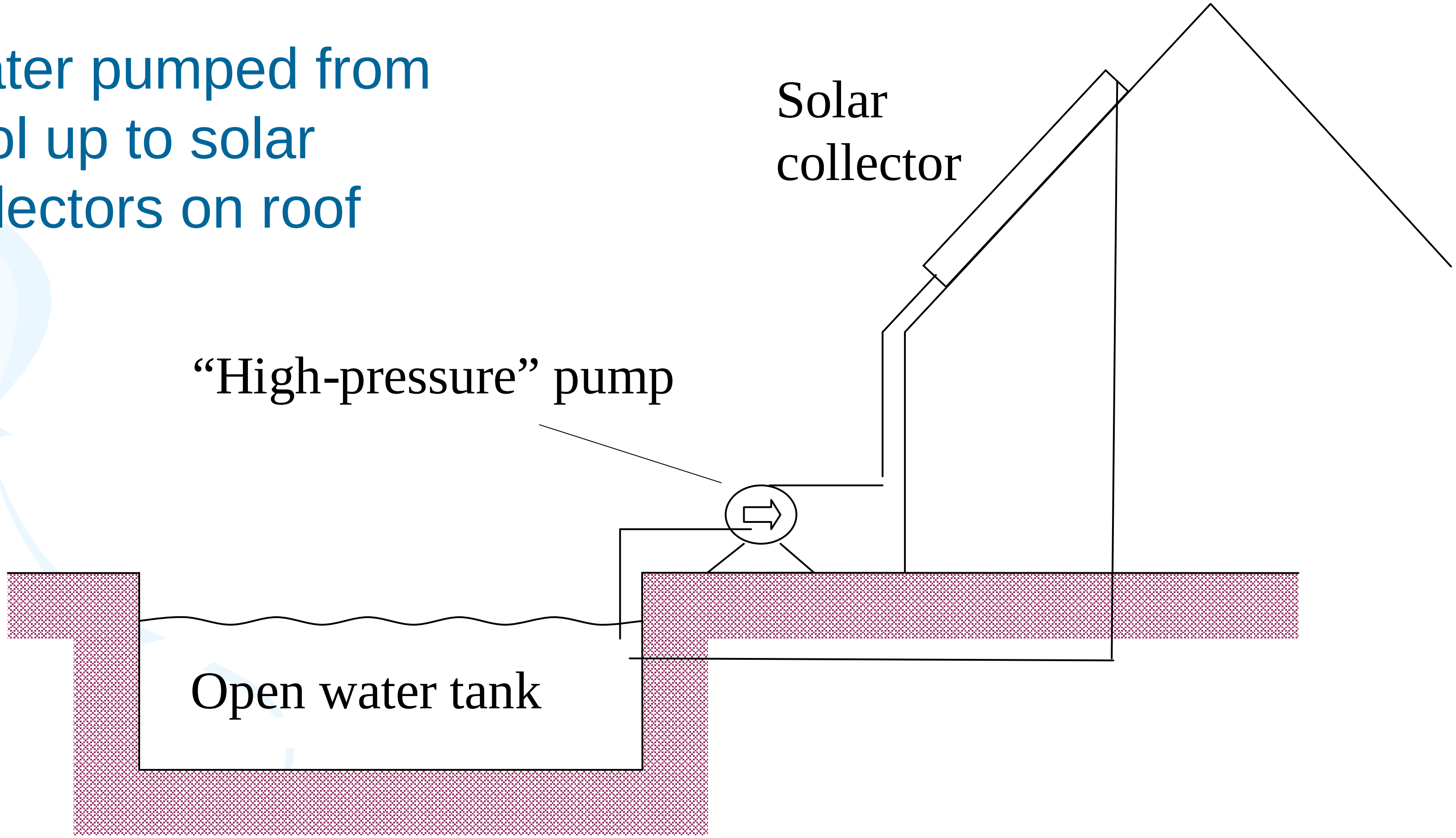
Thermosyphon (or natural circulation indirect solar water heating system



Swimming pool solar water heater

Water pumped from pool up to solar collectors on roof



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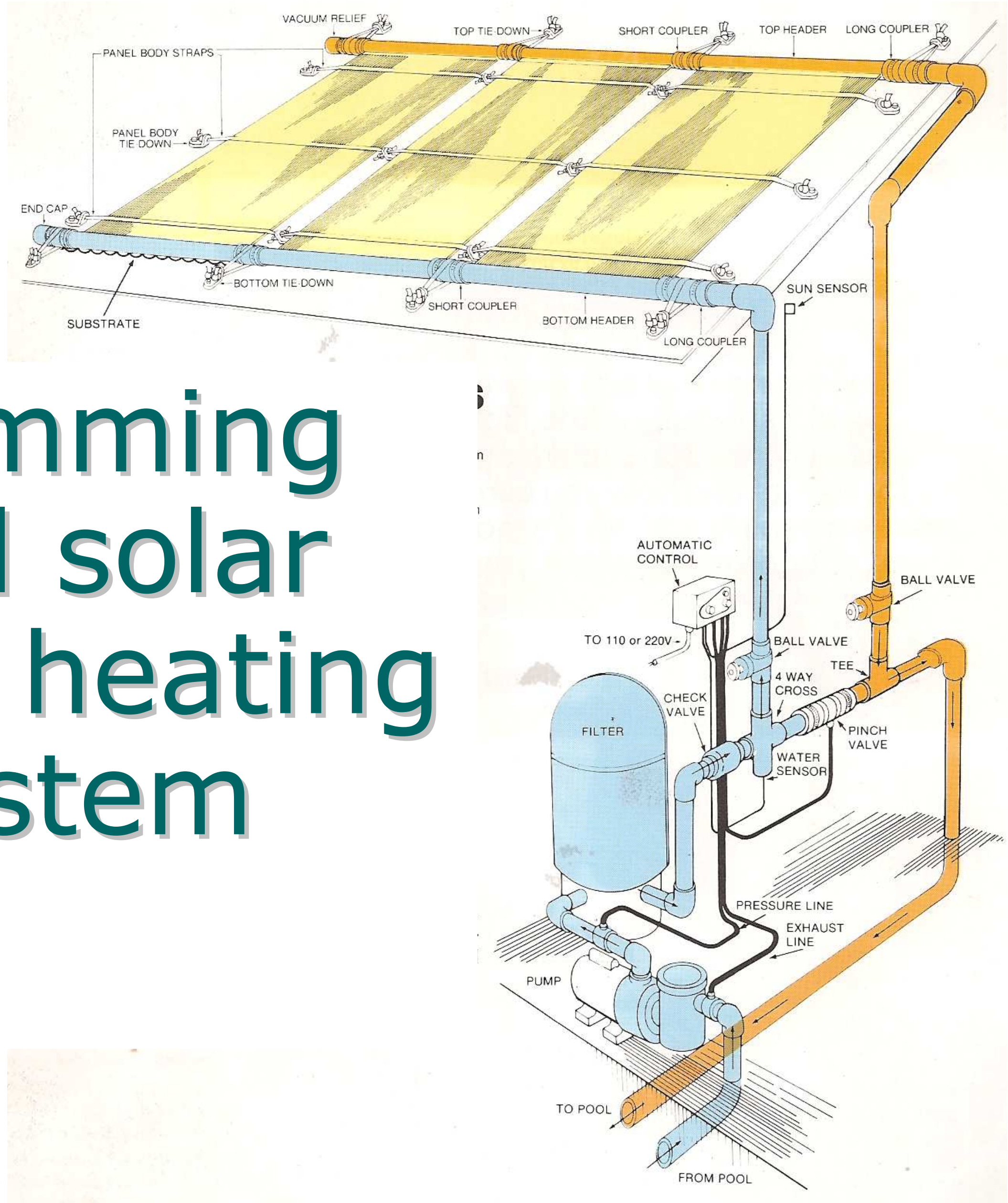
Swimming pool solar water heating system



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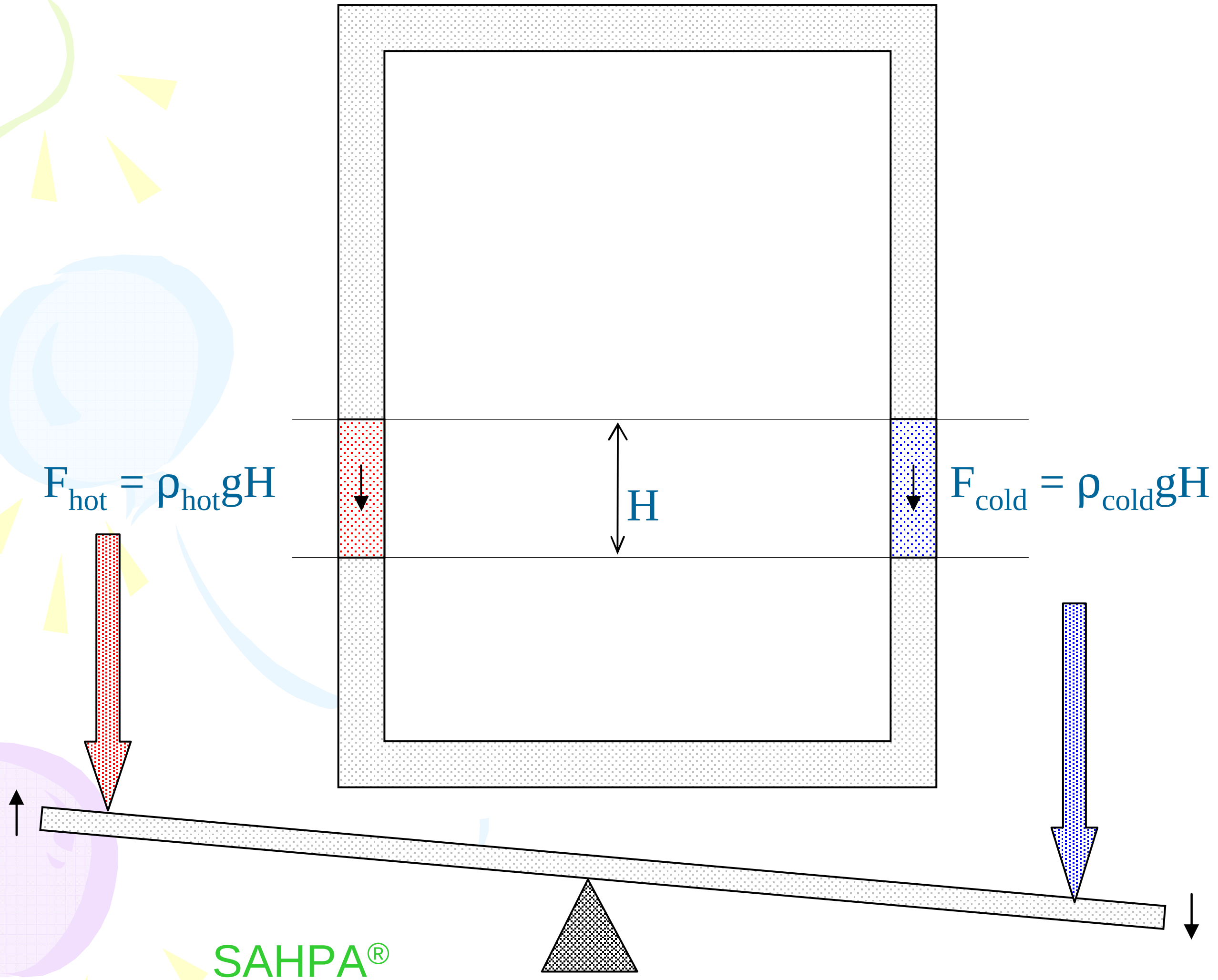
Thermosyphon solar water heating system

How does it work?



The density of the hot fluid is less than the density of the cold fluid. The force of attraction to the earth of the hot fluid is less than for the cold fluid. As a result of this force imbalance cold fluid sinks and the hot fluid rises and the fluid circulates around the loop. The denser or heavier fluid package will sinks and pushes the less-dense or lighter fluid up

Thermosyphon solar water heating system

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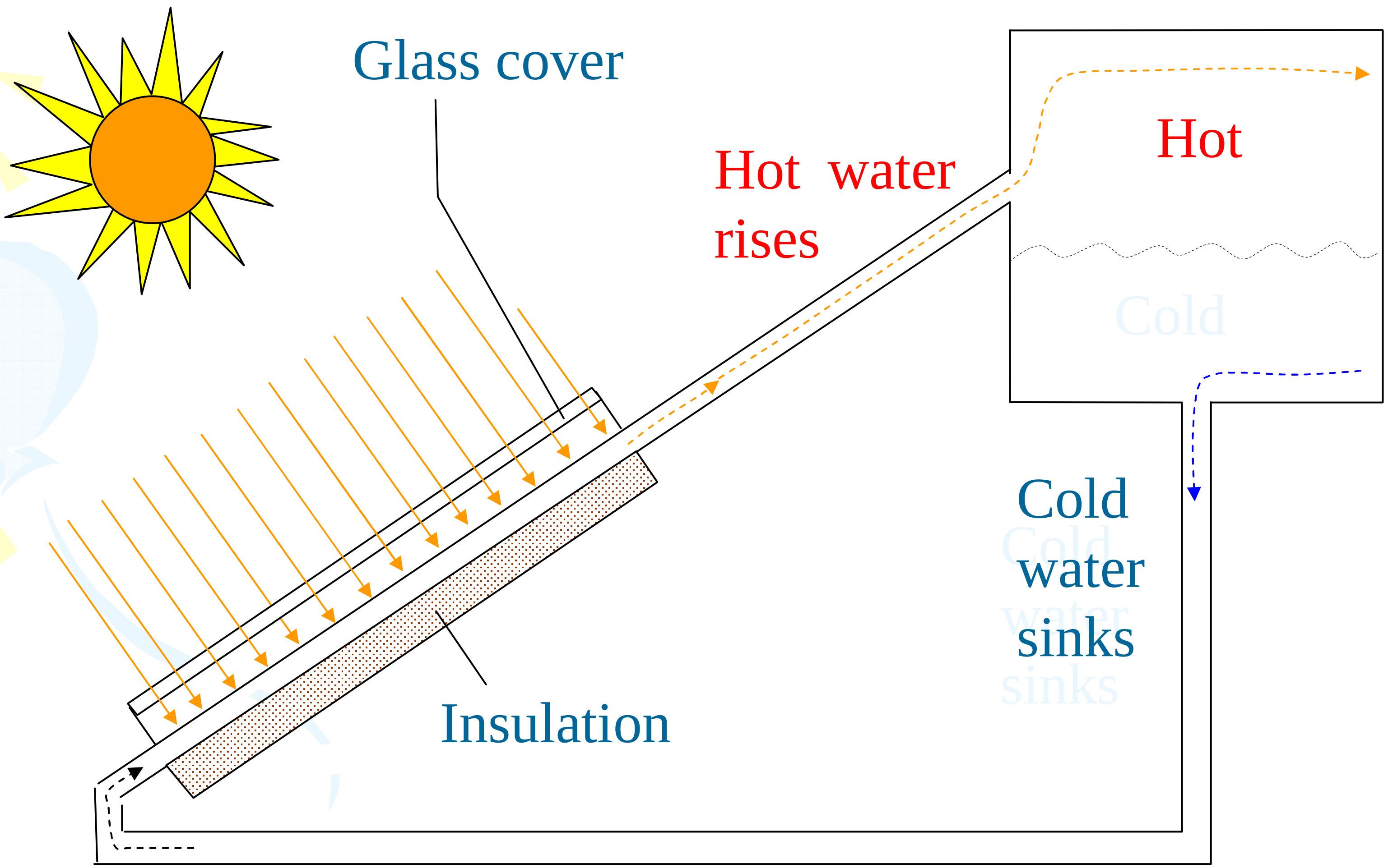

Basic theory: Divide the system into control volumes and apply the conservation of mass, momentum and energy

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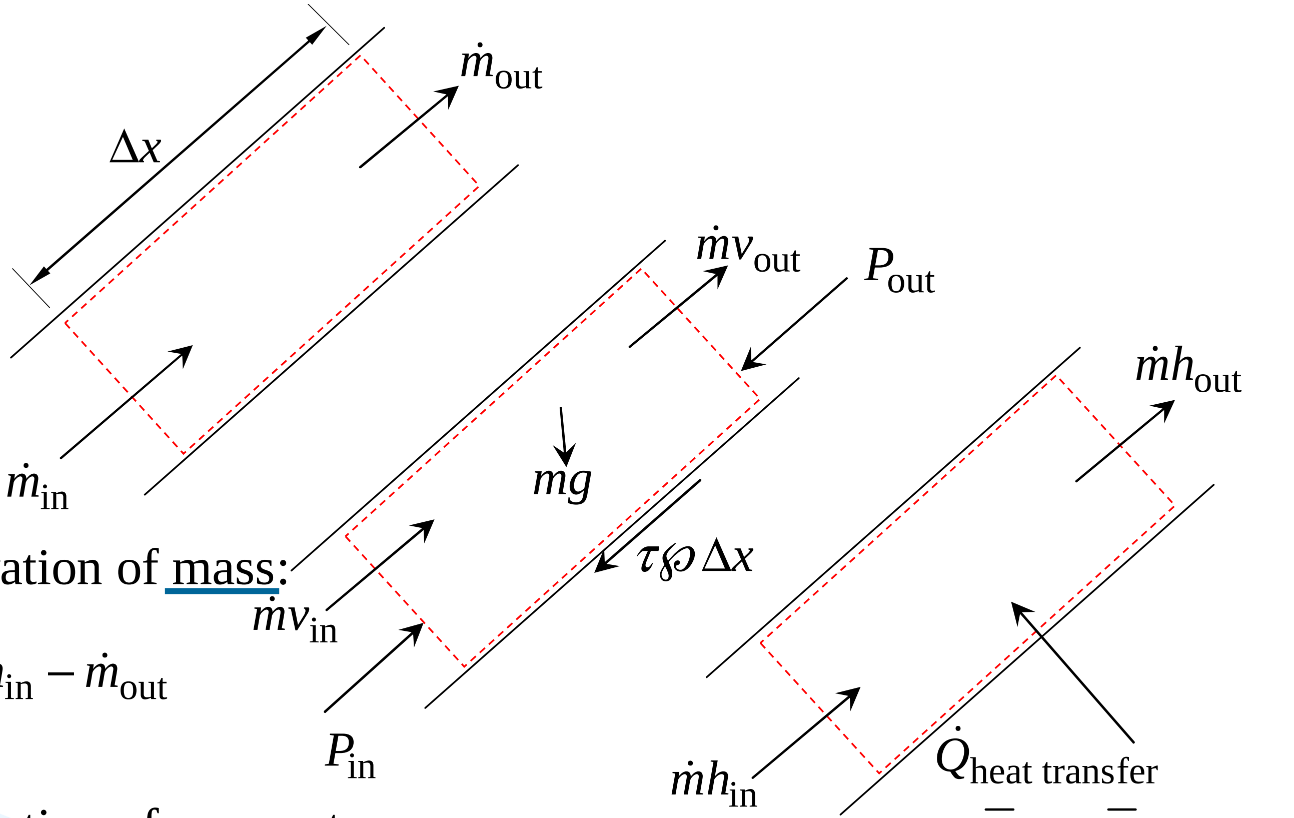

Conservation of mass:

$$\frac{\Delta m}{\Delta t} = \dot{m}_{in} - \dot{m}_{out}$$

Conservation of momentum:

$$\frac{\Delta mv}{\Delta t} = \dot{m}v_{in} - \dot{m}v_{out} - mg - \tau\wp\Delta x - (P_{out} - P_{in})A$$

Conservation of energy and heat transfer: $\frac{\Delta U}{\Delta t} = \dot{m}h_{in} - \dot{m}h_{out} + \dot{Q}_{heat\ transfer}$

Basic heat transfer theory:

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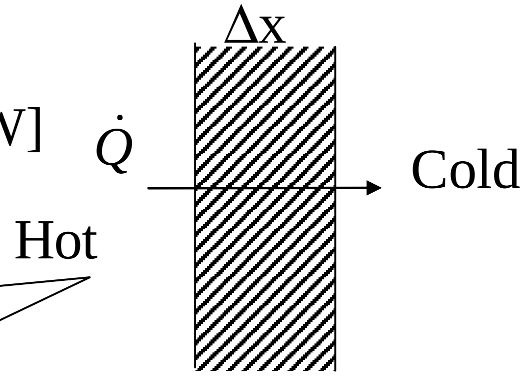
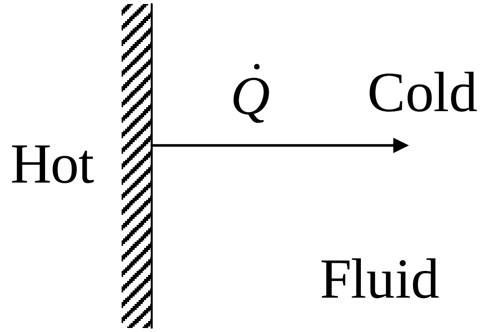
Heat transfer equation: $\dot{Q} = \dfrac{T_{hot} - T_{cold}}{R}$ [W]

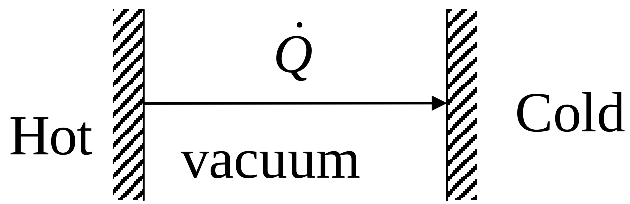


Conduction: $R = \dfrac{\Delta x}{kA}$ [°C/W]

Convection: $R = \dfrac{1}{hA}$ [°C/W]



Radiation: $R = \dfrac{1}{\varepsilon A \sigma \left((T_1 + 273)^2 + (T_2 + 273)^2\right)\left((T_1 + 273) + (T_2 + 273)\right)}$ [



Basic theory: Effect of glazing (glass)

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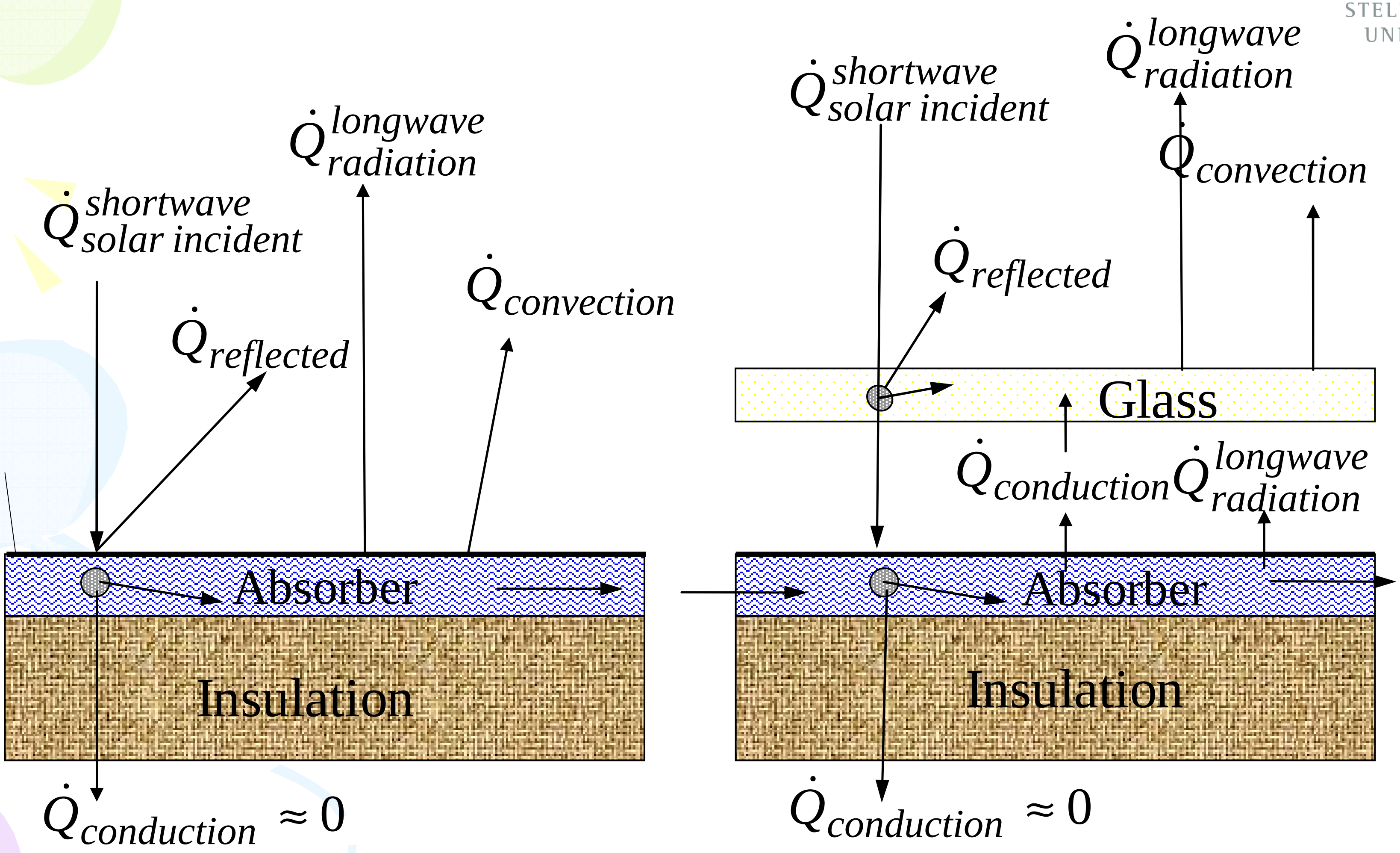

(a) No glass cover

(b) With glass cover plate

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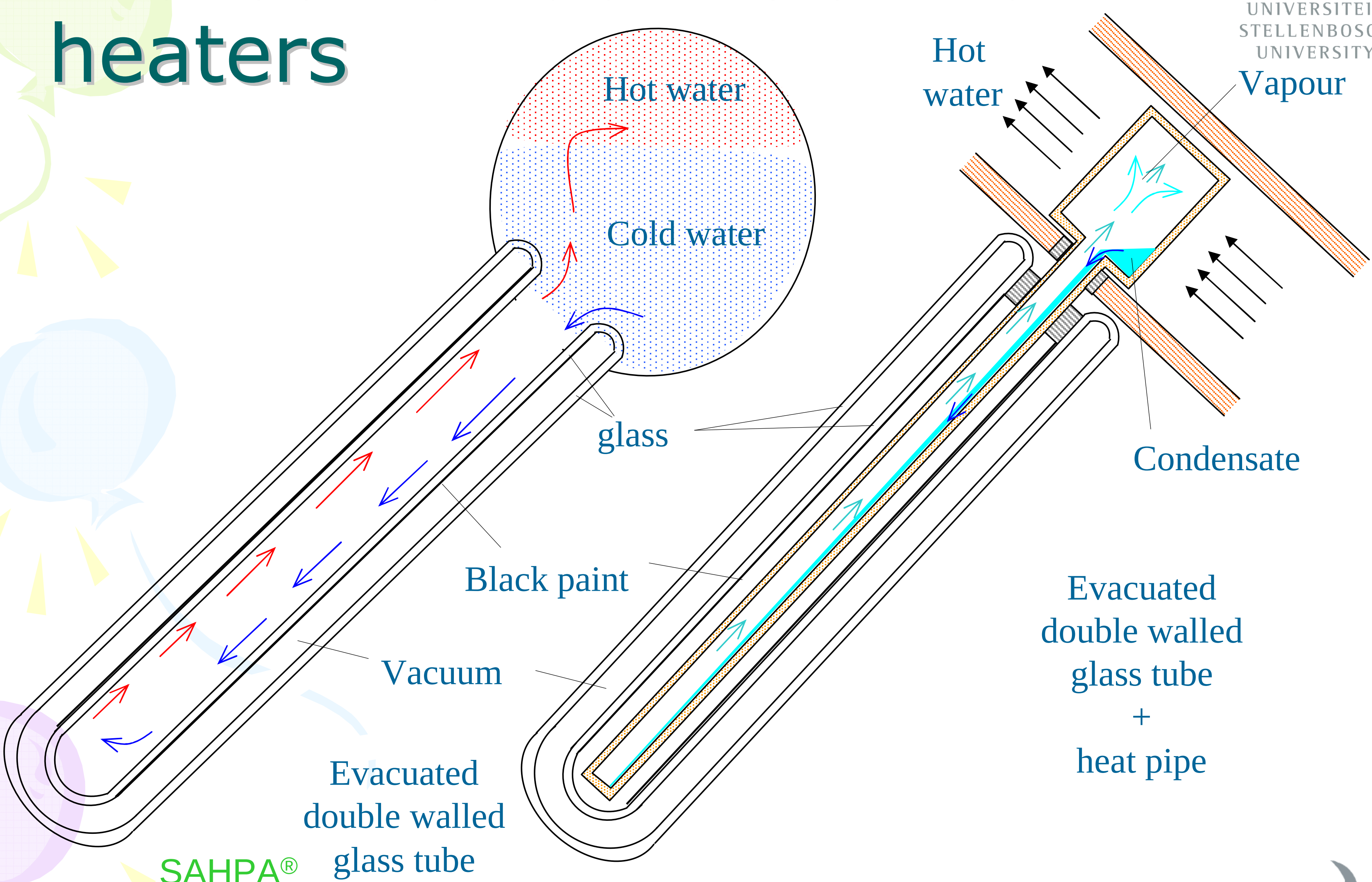
Evacuated-tube solar water heaters



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Typical domestic evacuated-tube solar water heater installation

Typical pumped indirect solar water heating system

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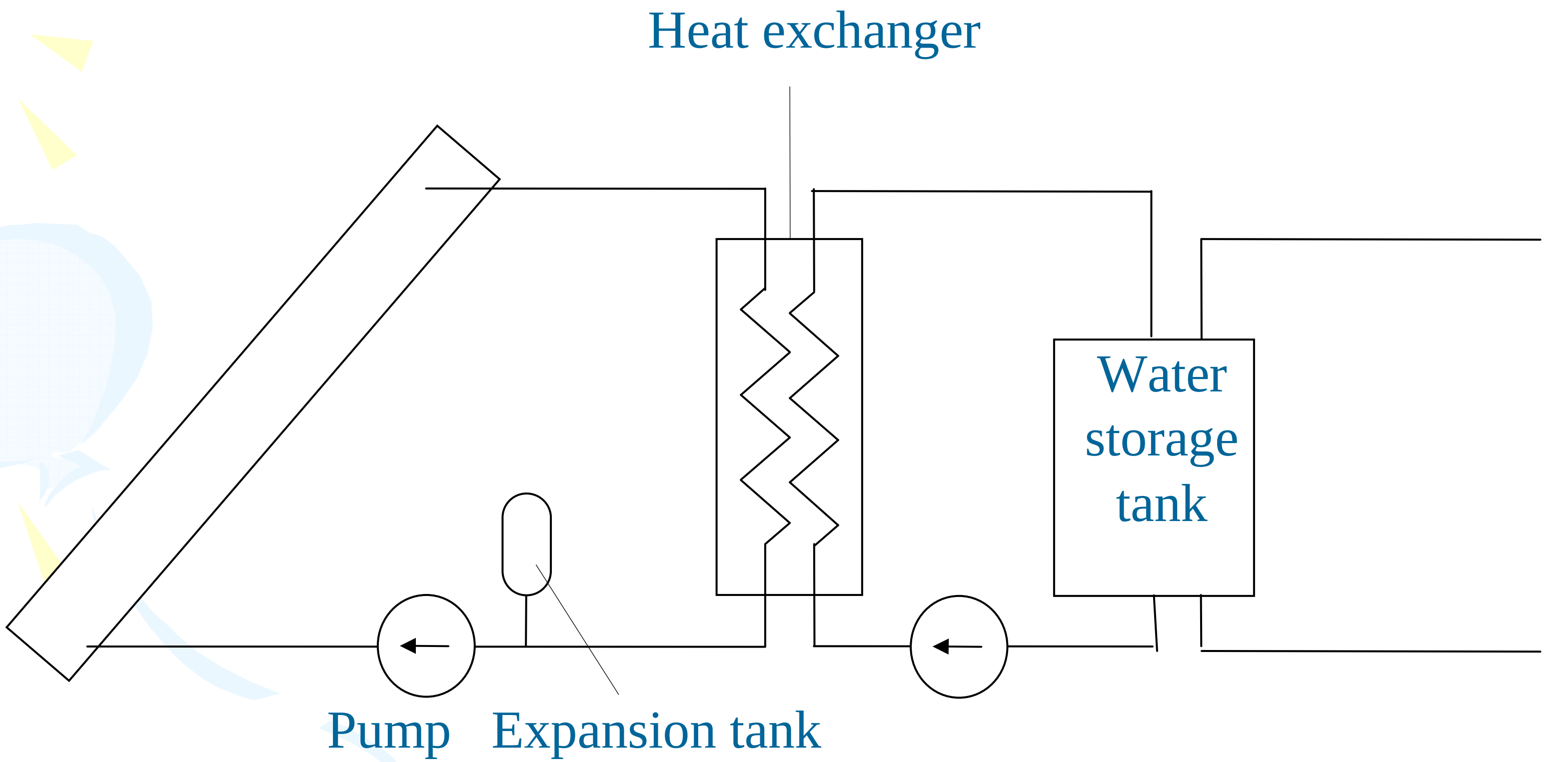
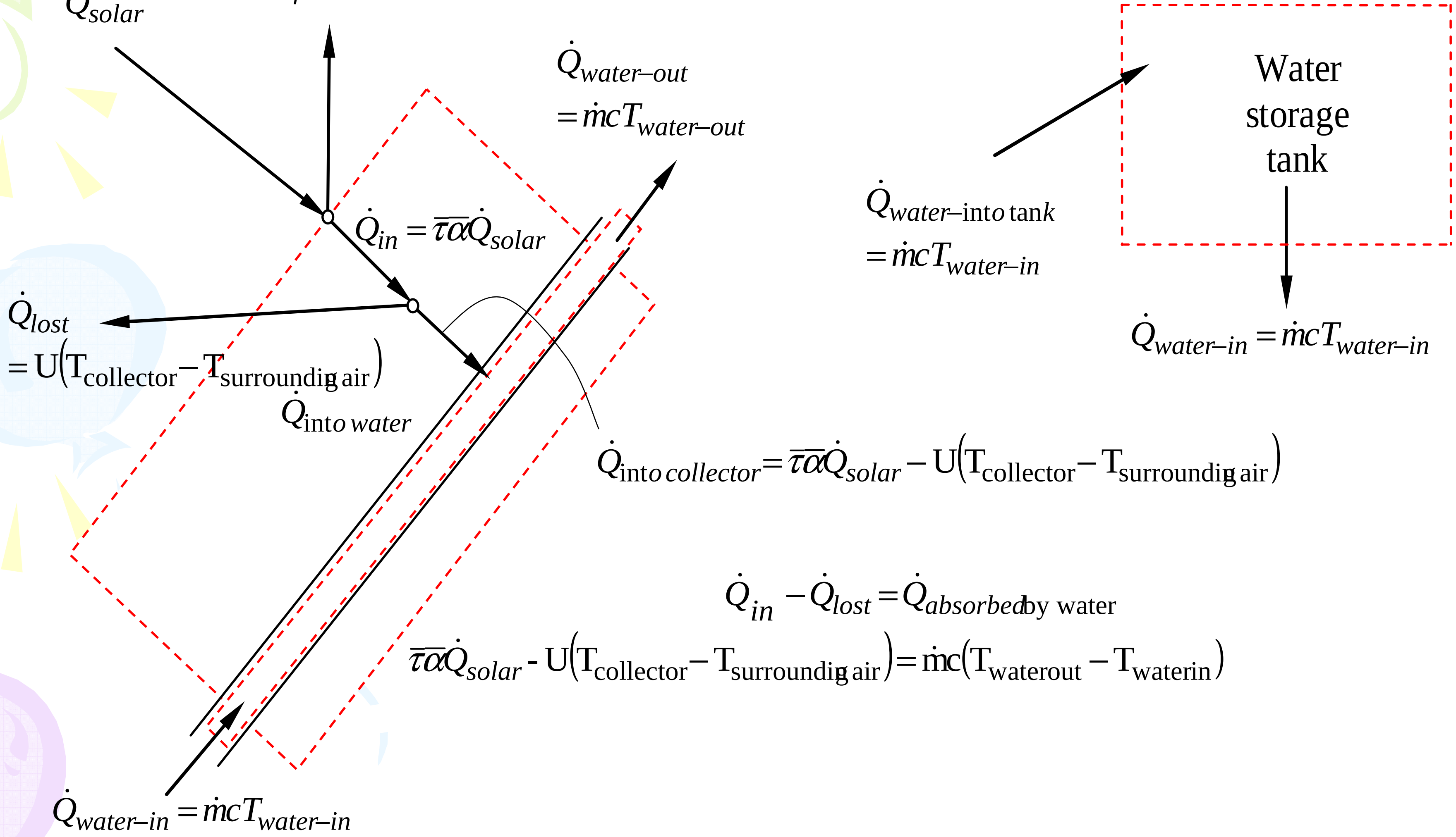


Basic theory: Heat collection

Heat storage



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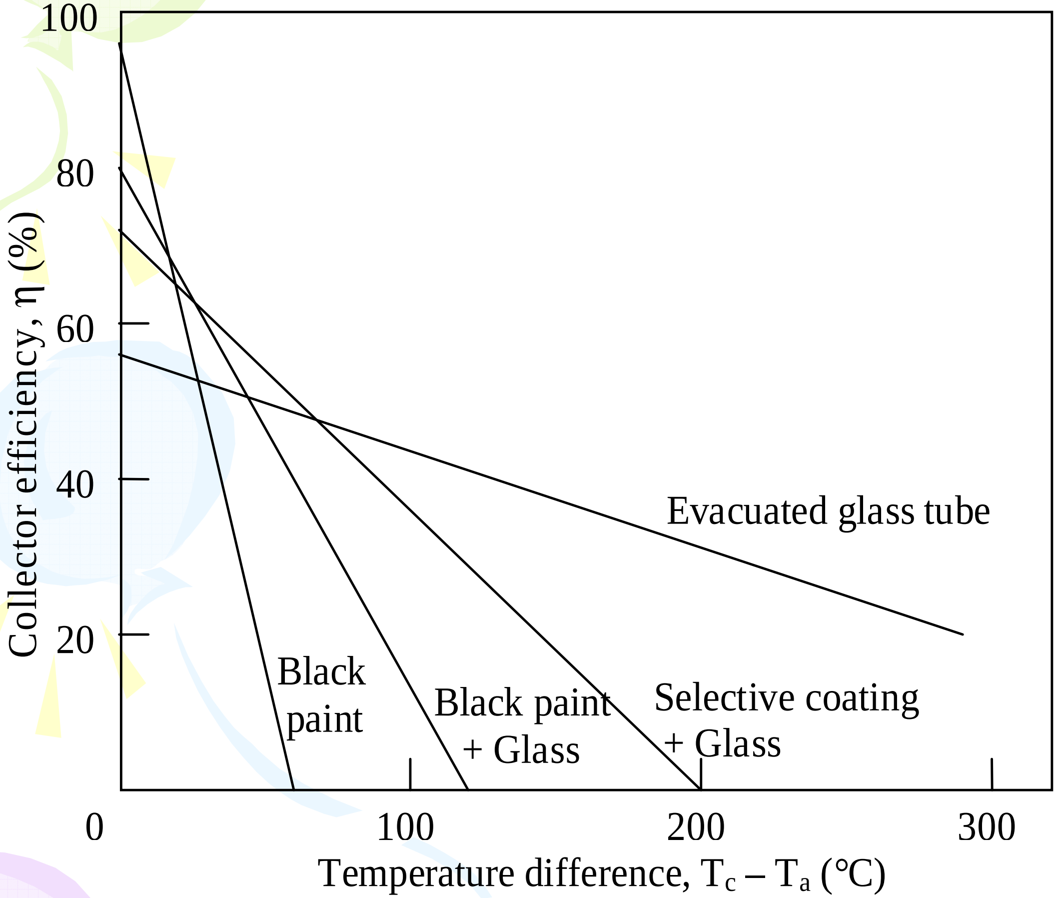
Typical solar water heater collector characteristics



where $T_c \approx \dfrac{T_{waterin} + T_{waterout}}{2}$

Solar collector thermal perfofmance characteristic is :

$$\eta = a + b(T_c - T_a)$$

where solar colloector efficiency $\eta = \dfrac{\dot{Q}_{collected}}{\dot{Q}_{input}}$

heat input factor $a = \dfrac{\dot{Q}_{input}}{\dot{Q}_{solar}} = \dfrac{\overline{\tau\alpha} \cdot \dot{Q}_{solar}}{\dot{Q}_{solar}} = \overline{\tau\alpha}$, and

heat loss factor $b = \dfrac{\text{heat collected}}{\dot{Q}_{solar}} = \dfrac{\overline{\tau\alpha} - U(T_{collector} - T_{surrounding\ air})}{\dot{Q}_{solar}}$

$$= \frac{\text{heat into water}}{\dot{Q}_{solar}} = \frac{\dot{m}c(T_{water\ out} - T_{water\ in})}{\dot{Q}_{solar}}$$

My rules!@#$%^&*()?:
Up to 40% electricity savings
50 % efficient
500 W/m^2 over an 8 hour period

Overheating??

Expansion relief??

Air bubbles??

Thanks

Automatic air relief??

Pressure??

Corrosion??

Freezing??

Gas loaded heat pipe temperature control??

Reverse thermosyphoning??

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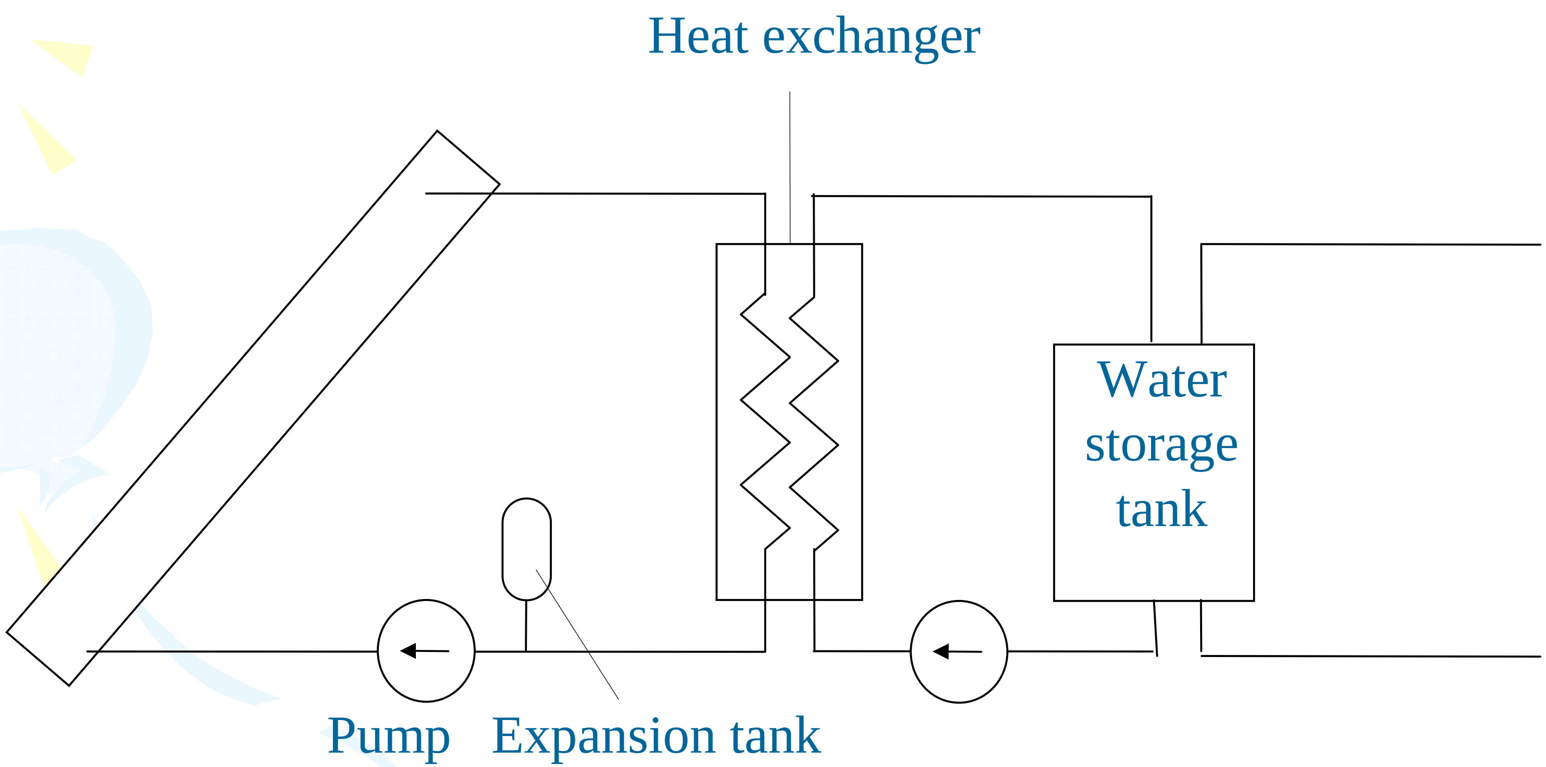
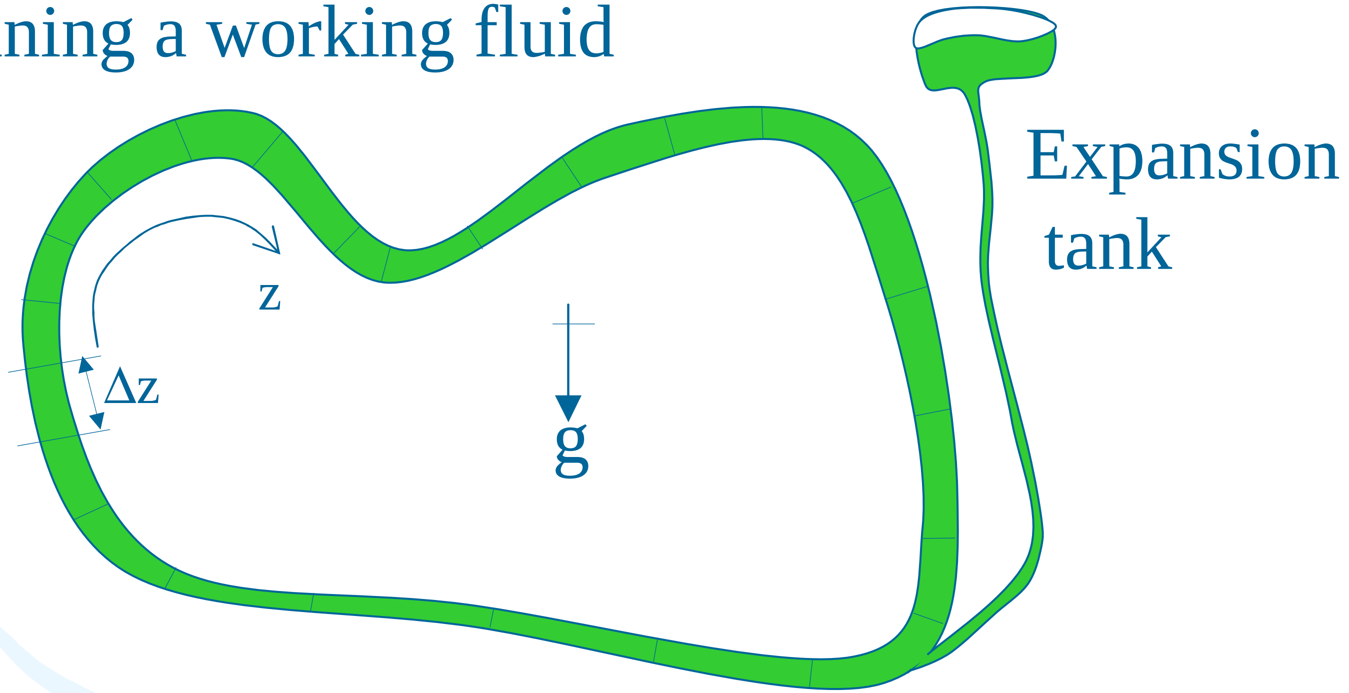
Typical pumped indirect solar water heating system



Theoretical modeling

Consider a hollow pipe with a variable diameter and fashioned into a closed loop and also containing a working fluid



Divide the loop up into a number of smaller control volumes, apply the equations of change to each control volume, and integrate around the loop!

Theoretical modeling (cont.)

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Conservation of Mass

Single phase flow $\frac{\Delta m}{\Delta t} = 0 = \dot{m}_{\text{in}} - \dot{m}_{\text{out}}$

Two-phase flow $\frac{\Delta m}{\Delta t} \neq 0 = \dot{m}_{\text{in}} - \dot{m}_{\text{out}}$ but mass enters the expansion tank instantaneously

Assumptions:

* One-dimensional flow $\dot{m} = \rho VA$
* Both liquid and vapour phases are incompressible
* Density (pressure) waves occur instantaneously, ie speed of sound >> $\dot{m}$

Theoretical modeling (cont.)

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Conservation of Energy

Single phase flow for the ith control volume with the temperature T expressed explicitly:

Heat transfer rate

$$T_i^{t+\Delta t} = T_i^t + \frac{\Delta t}{m_i^t c}\left(\dot{Q}_{\text{in,out}} + \dot{m}i_{\text{in}} - \dot{m}i_{\text{out}}\right)^t$$

$m = \rho A \Delta z$

i = enthalpy

c = specific heat

Theoretical modeling (cont.)

Conservation of Energy

Two-phase flow for the ith control volume with the temperature T expressed explicitly:

$$u_{\mathrm{i}}^{t+\Delta t} = u_{\mathrm{i}}^{t} + \frac{\Delta t}{m_{\mathrm{i}}^{t} c}\left(\dot{Q}_{\mathrm{in,out}} + \dot{m} i_{\mathrm{in}} - \dot{m} i_{\mathrm{out}}\right)$$

If $u^{t+\Delta t} < u_{\mathrm{f}}$ then $T_{\mathrm{hp}}^{t+\Delta t} = u^{t+\Delta t} / c_{v}$ and $x^{t+\Delta t} = 0$

If $u^{t+\Delta t} > u_{\mathrm{f}}$ then $T_{\mathrm{hp}}^{t+\Delta t} = T_{sat}$ and

$x^{t+\Delta t} = u^{t+\Delta t} - u_{f}^{t+\Delta t} / u_{fg}^{t+\Delta t}$, where $u_{\mathrm{hp}} = u_{\mathrm{f}} + x u_{\mathrm{fg}}$,

$i = i_{\mathrm{f}} + x i_{\mathrm{fg}}$, $u_{\mathrm{f}} = c_{\mathrm{v}} T_{\mathrm{hp}}$ and $i_{\mathrm{f}} = c_{\mathrm{p}} T_{\mathrm{hp}}$.

Theoretical modeling (cont.)

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Conservation of Momentum applied to heat pipe control volumes to determine the mass flow rate

Buoyancy driving term *Frictional-resistance term*

$$\frac{\mathrm{d}\dot{m}}{\mathrm{d}t} = -\frac{\sum_{k=1}^{N_k} \rho_{\mathrm{k}} L_{\mathrm{k}} \mathrm{g} \sin\phi_{\mathrm{k}}}{\sum_{k=1}^{N_k} \frac{L_{\mathrm{k}}}{A_{\mathrm{x,k}}}} - \frac{\sum_{k=1}^{N_k} \frac{C_{\mathrm{f},\ell\mathrm{o,k}} \phi_{\ell\mathrm{o,k}}}{\rho_{\mathrm{k}} r_{\mathrm{i,hp}}} \frac{L_{\mathrm{k}} + L_{\mathrm{f,equiv,k}}}{A_{\mathrm{x,k}}^2} \dot{m}^2}{\sum_{k=1}^{N_k} \frac{L_{\mathrm{k}}}{A_{\mathrm{x,k}}}}$$

Assumptions:

* Quasi-eqilibrium
* Both liquid and vapour phases are incompressible
* Homogeneous two-phase flow model
* Hydrostatic pressure at a point (Archimedes and Boussinesq ‘s approximation)

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