Heat Transfer Fluid for Concentrated Solar Systems

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Motivation
Introduction
Calculation of heat transfer coefficient
Results (liquid, gas, 2-phase)
New HTF
Conclusion
Heat transfer fluid (HTF) is a key component of concentrated solar systems that governs the working temperature of the thermodynamical cycles.

HTF may also be used as storage medium but it is used at least to extract heat from the storage tanks.

Heat transfer coefficient \((h)\) determines the wall temperature of the solar receiver for a given incident solar flux density (or power transfers to the HTF). The smaller \(h\) the larger absorbing surface area and cost. \(P = Sh(T_{wi} - T_{fb})\)
Power production

Radiation → *Heat Transfer Fluid* → Working Fluid

- **Concentrating System**
- **Solar Receiver**
- **Storage / Backup**
- **Power Block**
Some selection criteria for HTF

- Extended working temperature range and high thermal stability.

- Good heat transfer properties. For instance a large thermal conductivity ($k$) is desired for efficient heat transfer, and a low viscosity ($\mu$) is beneficial to pressure drop and pumping power. In addition, a large heat capacity ($cp$) would allow for direct thermal storage, although indirect solutions with a secondary medium are also possible.

- Low pumping energy losses and low vapor pressure

- Low hazard properties and large material compatibility

- Reduced cost
## Temperature limit of current HTF

<table>
<thead>
<tr>
<th>Heat transfer fluid</th>
<th>Temperature limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal oil</td>
<td>400°C</td>
</tr>
<tr>
<td>Molten salt (solar salt)</td>
<td>560°C</td>
</tr>
<tr>
<td>Air (gas)</td>
<td>More than 1000°C</td>
</tr>
</tbody>
</table>

Other HTF than air are needed at high temperature for advanced thermodynamic cycles.
Temperature limit of current liquid HTF

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>$T_{\text{melt}}$ ($^\circ$C)</th>
<th>$T_{\text{max}}$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermin VP-1</td>
<td>(C$<em>{12}$H$</em>{10}$) and (C$<em>{12}$H$</em>{10}$O). Percentage not know.</td>
<td>12</td>
<td>390</td>
</tr>
<tr>
<td>Solar Salt</td>
<td>wt. 60% NaNO$_3$/40% KNO$_3$</td>
<td>220</td>
<td>600</td>
</tr>
<tr>
<td>Hitec</td>
<td>wt. 53% KNO$_3$/7% NaNO$_3$/40% NaNO$_2$</td>
<td>142</td>
<td>454–538</td>
</tr>
<tr>
<td>Hitec XL</td>
<td>wt. 48% Ca(NO$_3$)$_2$/7% NaNO$_3$/45% KNO$_3$</td>
<td>133</td>
<td>500</td>
</tr>
<tr>
<td>NS-1</td>
<td>wt. 44% Ca(NO$_3$)$_2$/12% NaNO$_3$/44% KNO$_3$</td>
<td>127.6</td>
<td>622</td>
</tr>
<tr>
<td>NS-2</td>
<td>wt. 25.9% LiNO$_3$/20.0% NaNO$_3$/54.1% KNO$_3$</td>
<td>118</td>
<td>435</td>
</tr>
<tr>
<td>NS-3</td>
<td>wt. 30% LiNO$_3$/18% NaNO$_3$/52% KNO$_3$</td>
<td>120</td>
<td>550</td>
</tr>
<tr>
<td>NS-4</td>
<td>wt. 50-80% KNO$_3$/0-25% LiNO$_3$/10-45% Ca(NO$_3$)$_2$</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>NS-5</td>
<td>wt. 17.77% LiNO$_3$/15.28% NaNO$_3$/35.97% KNO$_3$/30.98% 2KNO$_3$ · Mg(NO$_3$)$_2$</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>NS-6</td>
<td>wt. 17.5% LiNO$_3$/14.2% NaNO$_3$/50.5% KNO$_3$/17.8% NaNO$_2$</td>
<td>99</td>
<td>500</td>
</tr>
<tr>
<td>NS-7</td>
<td>wt. 6% NaNO$_3$/23% KNO$_3$/8% LiNO$_3$/19% Ca(NO$_3$)$_2$/44% CsNO$_3$</td>
<td>65</td>
<td>561</td>
</tr>
</tbody>
</table>

Li C-J et al. AIMS Energy (2014), 2/2, 133
Temperature limit of liquid HTF

- LBE (PbBi)
- Na
- HITEC XL
- HITEC
- Solar Salt
- Thermal Oil

Temperature (°C)

0 200 400 600 800 1000 1200 1400 1600 1800

Thermal Oil
Solar Salt
HITEC
HITEC XL
Na
LBE

T (K)
## HTF for Future High Temperature cycles

<table>
<thead>
<tr>
<th>Thermodynamic Cycle</th>
<th>Cycle Efficiency</th>
<th>Overall Nominal Plant Efficiency</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Cycles (Rankine) 390°C-565°C</td>
<td>37% - 42%</td>
<td>20% - 23%</td>
<td>0 (Today technology)</td>
</tr>
<tr>
<td>Supercritical Steam ≥ 600°C</td>
<td>48%</td>
<td>27%</td>
<td>17% - 35%</td>
</tr>
<tr>
<td>Supercritical CO2 (Brayton) 600°C – 800°C</td>
<td>50% - 55%</td>
<td>28% - 31%</td>
<td>22% - 55%</td>
</tr>
<tr>
<td>Combined Cycle (Brayton/Rankine) 1300°C</td>
<td>60%</td>
<td>33.5%</td>
<td>45% - 67%</td>
</tr>
</tbody>
</table>

Overall efficiency: $\eta_{opt} \cdot \eta_{rec} \cdot \eta_{cyc} = 0.7 \times 0.8 \times \eta_{cyc}$
Heat transfer

\[ \Phi = h (T_W - T_F), \] the highest \( h \) the lowest \( T_w \)
Calculation of the heat transfer coefficient, $h$
To fluid

Losses

\[ \alpha I = q_{of} + h_{out}(T_{wo} - T_{amb}) + \varepsilon\sigma_b(T_{wo}^4 - T_{amb}^4) \]

\[ q_{of} = h_{cond}(T_{wo} - T_{wi}) \quad \text{W/m}^2 \]

\[ h_{cond} = \frac{2\lambda_w}{D \ln(D/d)} \]

\[ q_{of} = h_{in}(T_{wi} - T_f) \]

\[ -\lambda_f \left( \frac{dT}{dx} \right)_w = h_{in}(T_{wi} - T_f) \]
Data base for temperature dependent thermophysical properties: density ($\rho$), viscosity ($\mu$), thermal conductivity ($k$) and heat capacity ($C_p$).

Data for heat transfer calculation based generally on Nu versus Re and Pr correlations that depend of the flow conditions.

$$Nu = \frac{hd}{k}$$

$$Re = \frac{\rho v d}{\mu} \quad Turbulent \ flow: \ Re > 3000 - 10\,000$$

$$Pr = \frac{\mu C_p}{k}$$
Example for thermal oil

<table>
<thead>
<tr>
<th></th>
<th>382 °C</th>
<th>390 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>$\frac{J}{kg,K}$</td>
<td>2560</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$\frac{W}{m,K}$</td>
<td>0,0796</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$\frac{kg}{m^3}$</td>
<td>720</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$Pa,s$</td>
<td>0,0001562</td>
</tr>
</tbody>
</table>
Example for thermal oil

Four correlations available:

\[ \text{Nu}_1 = 0.023 \text{Re}^{0.8} P_r^{0.4} \quad \text{for} \quad 0.7 < P_r < 120 \]
\[ 10^4 < \text{Re} < 1.2 \times 10^5 \]
\[ \frac{L}{d} > 60 \quad \text{Dittus – Boelter} \]

\[ \text{Nu}_2 = 0.027 \text{Re}^{0.8} P_r^{\frac{1}{3}} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]
\[ \text{for} \quad 0.7 < P_r < 16700; \]
\[ \text{Re} > 10000; \]
\[ \frac{L}{d} > 60 \quad \text{(smooth pipes)} \quad \text{[Sider – Tate]} \]

\[ \text{Nu}_3 = 0.037 (\text{Re}^{0.75} - 180) P_r^{0.42} \left( 1 + \left( \frac{d}{L} \right)^{\frac{2}{3}} \right) \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]
\[ \text{for} \quad 2300 < \text{Re} < 10^6; \]
\[ 0.5 < P_r < 1000 \quad \text{[Hansen]} \]

\[ \text{Nu}_4 = 0.007 (\text{Re}^{0.87} - 280) P_r^{0.4} \left( 1 + \left( \frac{d}{L} \right)^{\frac{2}{3}} \right) \left( \frac{P_r}{P_r^w} \right)^{0.11} \]
\[ \text{for} \quad 2300 < \text{Re} < 10^6; \]
\[ 0.6 < P_r < 10^5 \quad \text{[Gnielinski]} \]

Heat transfer coefficient for liquids and gases
V = 2 m/s

T = 320°C
Thermophysical properties of solar salt

\[ C_p = 1443 + 0.172(T - 273.15) \quad \left[ \frac{J}{kg \, K} \right] \]

\[ \lambda = 0.443 + 1.9 \times 10^{-4}(T - 273.15) \quad \left[ \frac{W}{m \, K} \right] \]

\[ \rho = 2090 - 0.636(T - 273.15) \quad \left[ \frac{kg}{m^3} \right] \]

\[ \mu = \frac{22.14 - 0.12(T - 273.15) + 2.281 \times 10^{-4}(T - 273.15)^2}{1000} \quad [Pa \, s] \]
V = 1.8 m/s
Molten Salts

\[ V = 1.8 \text{ m/s} \]
$V = 1.8 \text{ m/s}$
Thermophysical properties of liquid sodium

Temperature range 97.8°C-873 °C (BP)

\[
C_p = 1658,2 - 8479 \times 10^{-4}T + 4454,1 \times 10^{-7}T^2 - 2992,6 \times 10^3T^{-2} \left[ \frac{J}{kg\,K} \right]
\]

\[
\lambda = 124,67 - 0,11381 T + 5,5226 \times 10^{-5}T^2 - 1,1842 \times 10^{-8}T^3 \left[ \frac{W}{m\,K} \right]
\]

\[
\rho = 219 + 275,32 \left( 1 - \frac{T}{2503,7} \right) + 511,58 \left( 1 - \frac{T}{2503,7} \right)^{0,5} \left[ \frac{kg}{m^3} \right]
\]

\[
\log(\mu) = -6,4406 - 0,3958 \log(T) + \frac{556,835}{T} \left[ \text{Pa\,s} \right]
\]
$V = 3.7 \text{ m/s, } T_{\text{max}} = 880^\circ\text{C}$
Pressurized Air

\[ T = 900^\circ \text{C}, \ 6 \ \text{atm.} \]
Pressurized He

The graph shows the variation of heat transfer coefficient $h$ (W/m².K) with temperature $T$ (K) for different pressures. The lines represent different pressures:

- $h_4$ (highest pressure)
- $h_3$
- $h_2$
- $h_1$ (lowest pressure)

The heat transfer coefficient decreases as the temperature increases for all pressures.
$V = 12 \text{ m/s}, \ 20 \text{ atm.}$
Influence of radiation on heat transfer

Simulation conditions:

- \( R = 2 \, \text{cm} \) and \( L = 2 \, \text{m} \)
- Inlet: for pure \( \text{CO}_2 \) at 400 K
- Inlet velocity: parabolic with a mean value of 1 m/s that leads to 0.0017 kg/s at 0.1 Mpa
- Tube wall: 1100K
- Pressure: from 0.1 MPa to 20 Mpa
- Reynolds number from 2 660 to 478 500 as a function of pressure
- Spectroscopic database: HITEMP-2010
- Line-by-line model used to derive a Absorption Distribution Function (ADF) global spectral model for computation

Influence of radiation on heat transfer

Evolution with pressure

Evolution with temperature
Influence of radiation on heat transfer

0.1 MPa

Without radiation

1 MPa

With radiation
The influence of radiation decreases with pressure.
Two-phase liquid-gas flow

water
Drawbacks: Instabilities in the phase change domain

Kandlikar, 1997
In most of the water/steam receivers, **the liquid water heating and evaporation part is separated from the steam superheating part** because they have different characteristics in terms of heat transfer which would result in high thermal stresses on the piping.

In the evaporation part of the process, another challenge is to control the boiling well enough so that most of the liquid is evaporated, avoiding energy losses due to the water recirculation, without reaching the **point of complete dryness. At this point the sudden drop of the heat transfer coefficient would provoke a violent increase of the tube temperature** and therefore threaten the integrity of the piping.
Two cases:
Case 1: 150 bar and 500 kW/m²: Point concentration
Case 2: 80 bar and 50 kW/m²: Linear concentration

Vertical versus horizontal pipes?

The flows are similar if Froude number is larger than 0.04

\[ Fr = \frac{G^2}{\rho_l^2 g D} > 0.04 \]

With \( G \): mass flux (kg/m².s), \( \rho_l \): liquid density, \( g \): gravity, diameter of the pipe.
Liquid water

\[ Nu_l = \frac{Re_{lo} Pr_l (f/2)}{1.07 + 12.7 (Pr_l^{2/3} - 1)(f/2)^{0.5}} \]

\[ Nu_l = \frac{h_l D}{\lambda_l} \]

\[ f = \left[ 1.58 \ln(Re_{lo}) - 3.28 \right]^{-2} \]

where \( Re_{lo} \) is the Reynolds number for liquid only, \( Pr_l \) is the liquid Prandtl number and \( f \) is the friction factor.

0.5 \( \leq \) Pr \( \leq \) 2000 and \( 10^4 \leq Re_l \leq 5 \times 10^6 \)

Petukhov and Popov (1963)
Heat transfer coefficient $h$ as a function of the bulk temperature $T_b$ for the liquid region, at a constant mass flux of 1444.4 kg/(m².s)
heat transfer coefficient $h$ as a function of the bulk temperature $T_b$ for the liquid region, at a constant velocity of 2 m/s
Heat transfer dominated by nucleated boiling in the fully developed boiling regime (FDB)

\[ h^* = 1058 \, Bo^{0.7} \, h_l \]

\[ q = h^* \, \Delta T_{sat} = h_{FDB} \, (\Delta T_{sat} + \Delta T_{sub}) \]

\[ Bo = \frac{q}{\dot{m} \, L_{lg}} \]

*Bo* the boiling number, \( \dot{m} \) is the mass flux

\( \Delta T_{sat} \) is the wall superheat defined by \( \Delta T_{sat} = T_{sat} - T_w \), \( T_{sat} \) is the saturation temperature, \( L_{lg} \) is the latent heat of vaporization

\( \Delta T_{sub} \) is the fluid subcooling defined by \( \Delta T_{sub} = T_{sat} - T_b \)
Pure steam

Subcooled Flow Boiling

C-E - Partial Boiling
E-G - Fully Developed Boiling
G-H - Significant Void Flow

Saturated Flow Boiling

Transition
Heat transfer coefficient as a function of the apparent thermodynamic quality $x_a$, from the liquid to the saturated boiling region, with a constant mass flux of 1444 kg/(m².s)

$$x = \frac{L_l - L_{l, sat}}{L_{l_g}} = -c_{p,l} \frac{\Delta T_{sub}}{L_{l_g}}$$

$L_l$ the specific enthalpy of the liquid, $L_{l, sat}$ the specific enthalpy of the liquid at the saturation temperature and $L_{l_g}$ the latent heat of vaporization
Heat transfer coefficient $h$ as a function of the bulk temperature $T_b$ for the steam region, at a constant velocity of 15 m/s.
New heat transfer fluid: solid particles
New HTF is needed with:

- Wide operating temperature range (as air),
- Acceptable wall-heat transfer coefficient,
- Small energy need for pumping,
- High value of heat capacity,
- No freezing limitation,
- No environmental impact and safety issues,
- Double use as HTF and storage medium
<table>
<thead>
<tr>
<th></th>
<th>Particle Dense Suspension (PDS)</th>
<th>Circulating Fluidized Bed (CFB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle volume ratio</td>
<td>30-40%</td>
<td>3-5%</td>
</tr>
<tr>
<td>Gas velocity</td>
<td>&lt; 0.1 m/s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Mechanical energy</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube erosion, particle</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>attrition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h_{\text{wall-to-bed}}$</td>
<td>Good</td>
<td>Low</td>
</tr>
</tbody>
</table>
The hydrostatic pressure of the suspension ($\Delta P_{\text{static}}$), which is the sum of the gas pressure drop across the bed and the gas hydrostatic pressure, maintains the balance with the flow driving force ($\Delta P_{\text{motor}}$) thus raising the bed level in the tube ($h_{\text{tube}}$). At equilibrium it comes,

$$\Delta P_{\text{static}} = \left(\frac{\Delta P}{L} + \rho_g g\right)(h_{\text{tube}} - h_{\text{chamber}}) = (\alpha_p \rho_s + \varepsilon \rho_g)g(h_{\text{tube}} - h_{\text{chamber}})$$

$$\Delta P/L = (\alpha_p \rho_s + \varepsilon \rho_g)g - \rho_g g = \alpha_p (\rho_s - \rho_g)g$$

Pressurized vessel with fluidized particles at $P_{\text{chamber}}$

Upward flow of particles
Opaque metallic tube (dia 42.4 mm, height 1 m)  2/ Dispenser fluid bed  

Heat transfer coefficient versus mean particle velocity (particle volume fraction $0.29 < \alpha_p < 0.32$)
The problem of heat transfer coefficient calculation in the DSP tube

How to calculate $h$?

Particle buffer tank

Irradiated tube

Main upward flow

Secondary downward flow
Last results, June 23 2014: a 750°C HTF

Solid suspension temperature as a function of time (blue: inlet, red: outlet); average solid mass-flow rate 32 kg/h ($T_{p,o}$ Outlet particle temperature; $T_{p,i}$ Inlet particle temperature).
<table>
<thead>
<tr>
<th>HTF</th>
<th>Lim. Temp.</th>
<th>$H$ (W/m².K)</th>
<th>Safety/Env.</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal oil</td>
<td>400°C</td>
<td>Medium 1000-4000</td>
<td>Hazardous molecule. Fire hazard</td>
<td>Cost</td>
</tr>
<tr>
<td>Molten salt</td>
<td>560°C</td>
<td>High 5000-9000</td>
<td>Strong oxidizing components. Decomposition at HT.</td>
<td>Freezing at temperature below 150-240°C</td>
</tr>
<tr>
<td>Molten metals</td>
<td>880°C for Na metals</td>
<td>Very high 20 000-40 000</td>
<td>Explosive with $H_2O$</td>
<td>Strong chemical constraints</td>
</tr>
<tr>
<td>Air</td>
<td>More than 1000°C</td>
<td>Small 200-400</td>
<td>no</td>
<td>Small heat capacity</td>
</tr>
<tr>
<td>CO₂</td>
<td>More than 1000°C</td>
<td>Small but higher than air 400-700</td>
<td>No if CO production is avoid</td>
<td>Radiation may increase h Supercritical cycles Small Cp</td>
</tr>
<tr>
<td>Water/Steam</td>
<td>Up to 565°C</td>
<td>From very high to medium for steam</td>
<td>High pressures</td>
<td>Instabilities that may lead to tube breaking</td>
</tr>
</tbody>
</table>
We are developing new stable HTF for low and high temperature applications

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