ESTATE project
A first analysis of the solar trough transient

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1. Introduction

The CSP technology is based on the concentration of direct solar irradiation; this source of power is subject to a high variability with time due for instance to the weather conditions.
A sudden change in the direct solar irradiation turns into a variation in the power transferred to the heat-collecting element and to fluid used as a coolant.
The whole system therefore needs to be regulated and controlled by changing the mass flow rate of the cooling fluid or by defocusing the parabolic mirrors.
It is interesting to know what are the time scales of the system, to evaluate the needs of the control system, and estimate the system behavior when no control system is present.
The system is characterized by a heat capacity given by the sum of the heat capacity of the steel tube and of the working fluid inside.

2. Transient analysis

The system behavior may be described with a sufficient accuracy by the following system of equations, where the main approximations are in the fact that an uniform irradiation of the tube is assumed, so that the tube temperature is constant for each section, and that the heat losses are only dye to the infrared irradiation.

$$q_{sun} - q_{loss} = \rho_{tube} c_{tube} \frac{\pi}{4}(D_e^2 - D_i^2)\frac{dT_{tube}}{dt} + q_{fluid}$$

$$q_{fluid} = \rho_{fluid} c_{fluid} \frac{\pi}{4} D_i^2 \left(v_{fluid} \frac{dT_{fluid}}{dx} + \frac{dT_{fluid}}{dt} \right)$$

$$q_{fluid} = h\pi D_i (T_{tube} - T_{fluid})$$

$$q_{loss} = \varepsilon\sigma\pi D_e T_{tube}^4$$

$T_{tube}(x,t)$ and $T_{fluid}(x,t)$ are the mean temperature for tube and the fluid in a given section, q_{sun} is the sun thermal power per unit length on the pipe external surface, q_{loss} is the power loss for the irradiation and q_{fluid} is the power per unit length transferred to the fluid.
The mass flow rate of the coolant is varied as a function of the irradiation from the sun, so that the temperature at the outlet is maintained constant in time.
Let us supposed as a possible scenario, that the irradiation varies instantly from the design value to zero, for instance for the shading of a cloud, with the system initially in equilibrium condition.
Let us compare four different systems:

- The molten salt system of ENEA
- The Helium system of CRS4
- The Helium system with an additional swirl tape
- The Helium system with a double thickness tube

The properties of the system are chosen to have the same temperature limits for the three systems, and are summarized in the following table

		Salt	Helium	He swirl	He thick	
Sun power	q_{sun}	5000	5000	5000	5000	kW/m
Tube length		4.06	4.06	4.06	4.06	m
Tube number		24	24	24	24	-
Tube ext. diameter	D_e	70	70	70	70	mm
Tube int. diameter	D_i	64	64	64	58	mm

Tube tape thickness		-	-	3	-	mm
Tube emissivity	ε	0.16	0.16	0.16	0.16	-
Tube density	ρ_{tube}	7960	7960	7960	7960	kg/m^3
Tube spec. heat	c_{tube}	500	500	500	500	J/kgK
Fluid density	ρ_{fluid}	2110	~2	~2	~2	kg/m^3
Fluid spec. heat	c_{fluid}	1529	5193	5193	5193	J/kgK
Minimum temp.	T_{min}	270	270	270	270	°C
Maximum temp	T_{max}	543	543	543	543	°C
Mass flow rate	m_{fluid}	1.037	0.306	0.306	0.306	kg/s
Temp. max. rate	$\dot{T}_{max}$	22	109	86	61	°C/min

The heat exchange coefficient has been calculated on the basis of the smooth tube theory, with the suitable correction for the swirl tape effect. The values of conductivity and viscosity are temperature dependent and are not listed here for brevity.
A numerical simulation of the system was run, by means of a simple numerical code. An explicit forward Euler time advancing scheme is adopted.
The simulated period is one hour, for the first half the design value of the solar power is acting, then for the second half the solar irradiation is dropped to zero.
The mass flow rate is kept constant and initially the fluid and the tube are at the inlet temperature conditions.
The following figures show the temperature variation of the fluid in four tubes of the trough line for a molten salt mixture and for the high-pressure helium.

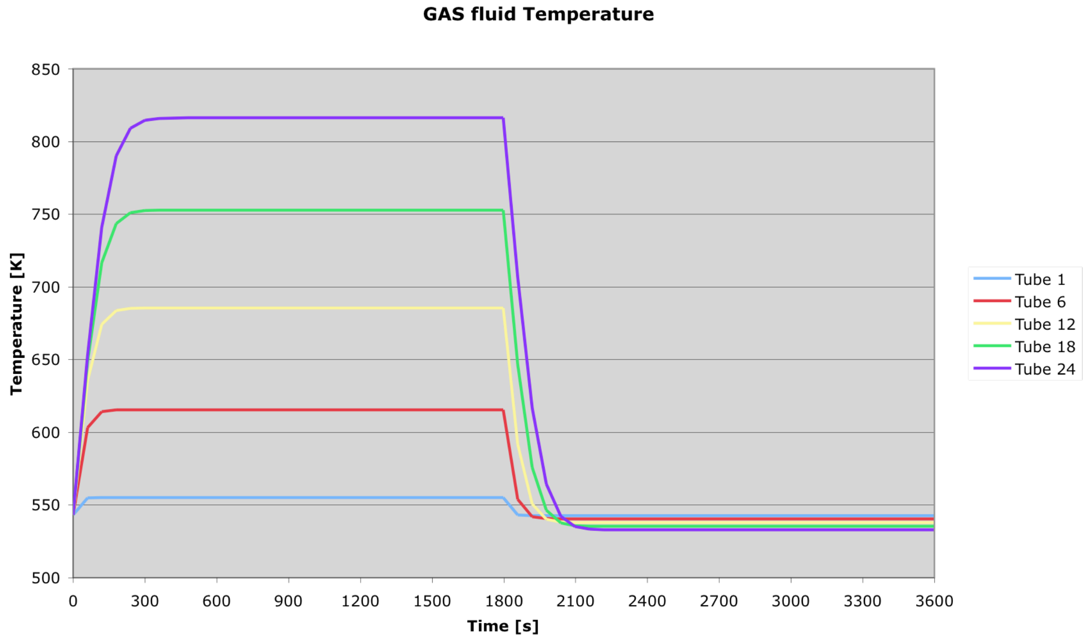

Figure 1 Helium temperature in the trough

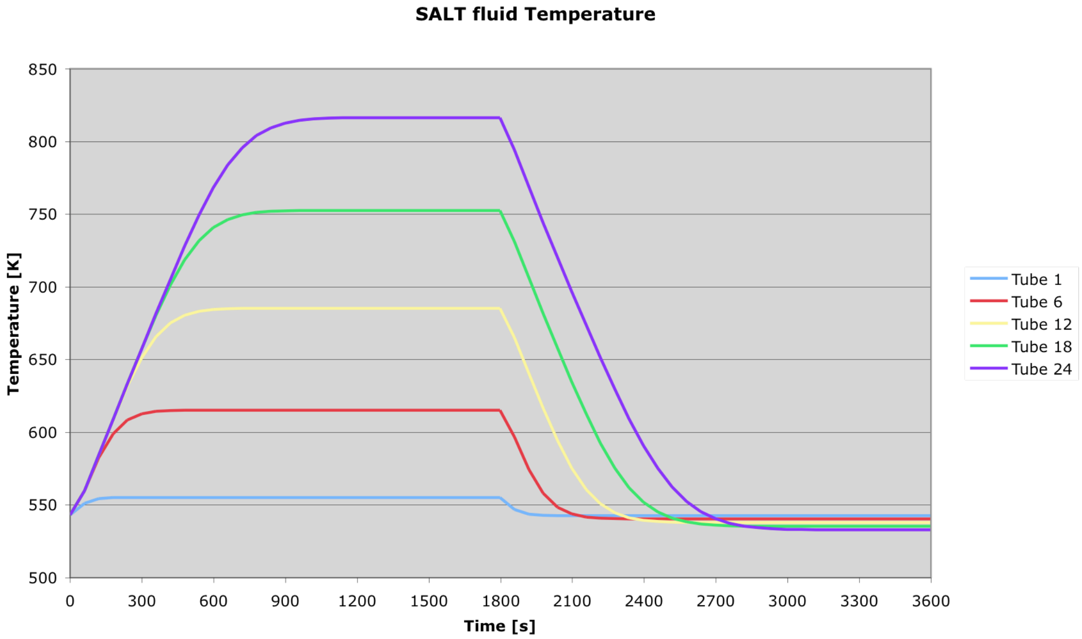

Figure 2 Molten salt mixture temperatures in the trough

It is apparent from the previous figures that the thermal inertia of the molten salt system is much higher than that of the gas system. When the solar irradiation is dropped to zero, the maximum temperature reached by the fluid decreases by 109K in the first minute for the helium and by only 22K for the molten salt system. The system is cooled down completely in 5 minutes when helium is used and in 15 minutes with the molten salt mixture.

This datum may be negative for the gas from the point of view of the control system, since it is required to operate quicker. But it is also true that the gas system reaches the operating temperature quickly without the necessity of excessively long heat up periods.

The comparison between mean fluid and tube temperature for the last tube portion of the trough line is showed in the following figure, where the difference in the transient time is even more evident. It can also be noted that the temperature difference between the tube and the fluid is almost equal for the two coolant fluids, which may therefore be considered as equivalent in their cooling efficiency.

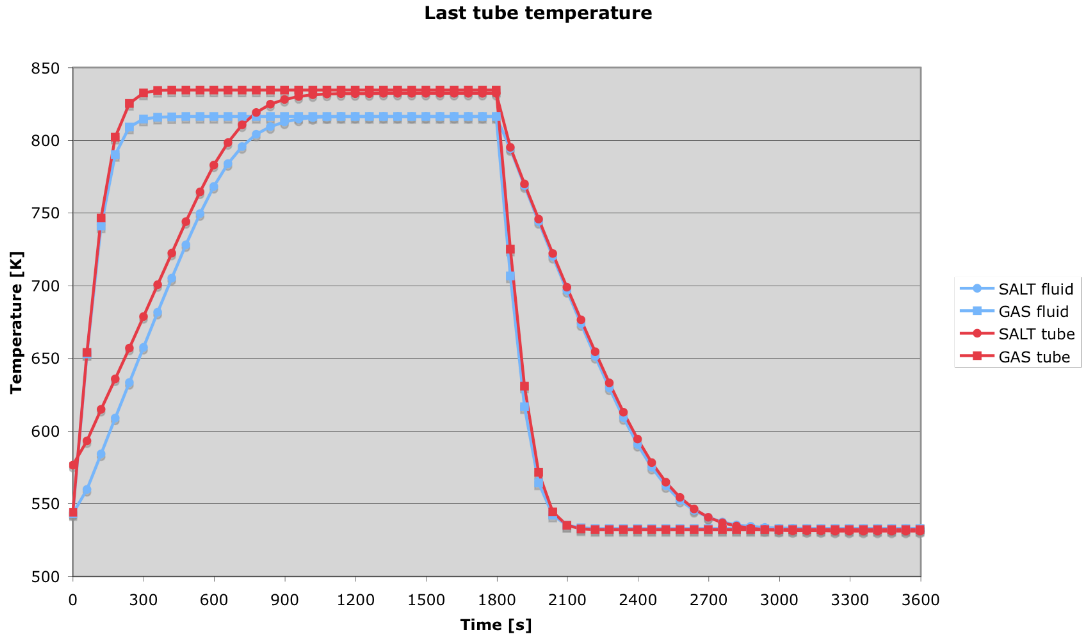

Figure 3 Comparison between the mean tube and fluid temperatures for the last module of the trough line, for a molten salt system and for a pressurized helium system

The swirl tape that may be inserted of the absorber tube has the function to increase the heat exchange coefficient, but also increases the heat capacity of the tube. The following figure shows the differences for two systems using helium, with and without the swirl tape. In the first minute when the sun power is dropped to zero the maximum temperature of the system with the swirl tape is dropped by 86K instead of 109K, still far from the performances of the system with molten salt.

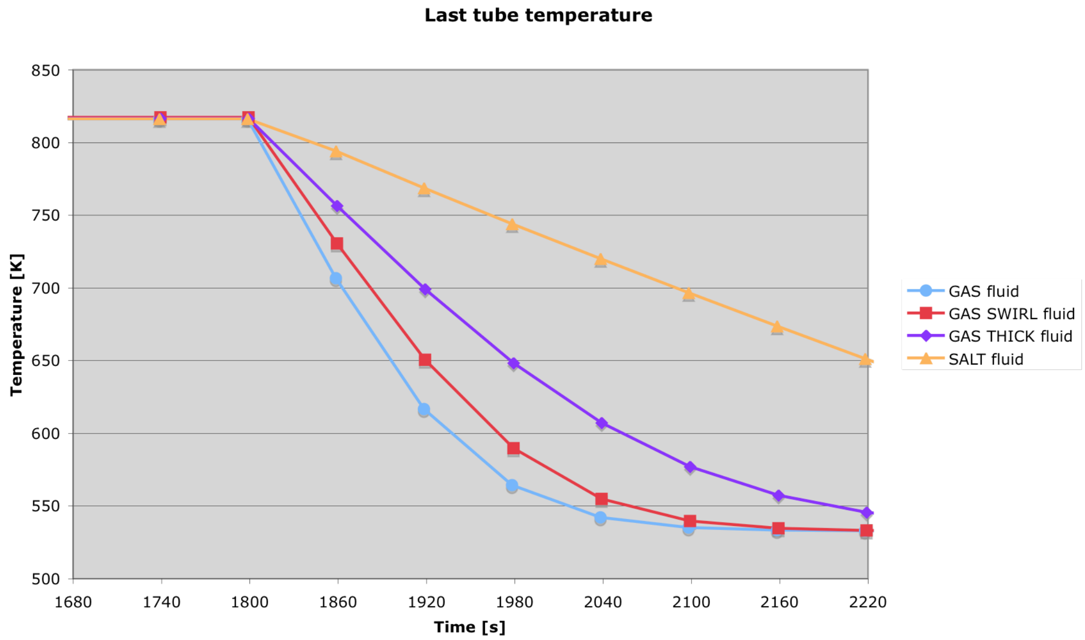

Figure 4 Comparison between the mean fluid temperatures for the last module of the trough line, for the four systems analyzed

3. Simplified model

A rough approximation of the system performance may be obtained with a simple 0D model. When the sun irradiation ceases, the portion of the tube is cooled with a rate approximately equal to the sun power, while the heat capacity may be approximated with the sum of the tube and the fluid heat capacity; the tube and fluid temperatures are taken as equal.

$$\frac{dT}{dt} = -\frac{q_{sun}}{\rho_{tube} c_{tube} A_{tube} + \rho_{fluid} c_{fluid} A_{fluid}}$$

The following table summarizes the results:

		Salt	Helium	He swirl	He thick	Oil	
Sun power	q_{sun}	5000	5000	5000	5000	5000	kW/m
Tube density	ρ_{tube}	7960	7960	7960	7960	7960	kg/m^3
Tube spec. heat	c_{tube}	500	500	500	500	500	J/kgK
Tube section	A_{tube}	6.31	6.31	8.23	12.06	6.31	cm^2
Fluid density	ρ_{fluid}	2110	~1.2	~1.2	~1.2	~765	kg/m^3
Fluid spec. heat	c_{fluid}	1529	5193	5193	5193	~2700	J/kgK
Fluid section	A_{luid}	32.17	32.17	30.25	26.42	32.17	cm^2
Temperature rate	$\dot{T}$	23.3	118.5	91.1	62.1	32.8	°C/min
Simulated rate	$\dot{T}_{max}$	22	109	86	61	-	°C/min

The results obtained with the simplified model are almost equal to the results of the simulation. In the previous table the data relative to an system using an oil as heat transfer fluid; this data has been introduced for a comparison since the oil cannot reach the same temperature range of the gas and salt systems.

4. Controlled transient

In a real application the mass flow rate wouldn't be kept constant and independent from the sun irradiation value; some control is present on the mass flow rate of the working fluid, to reduce the variations of the outlet fluid conditions.
As an example let us suppose that the mass flow rate is reduced by a factor of 10 when the sun irradiation ceases, and have a look at the variations of the fluid and steel temperature for the last tube of the through line; for both the salt and gas systems.

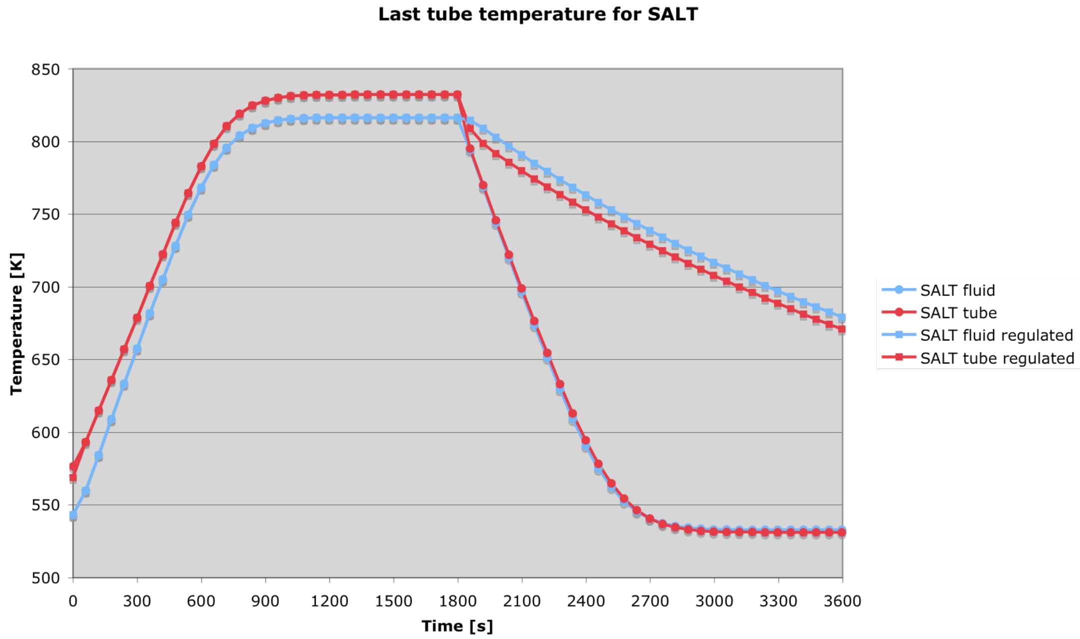

Figure 5 Fluid and steel temperature variation in the last tube for the salt system, with and without the change in mass flow rate

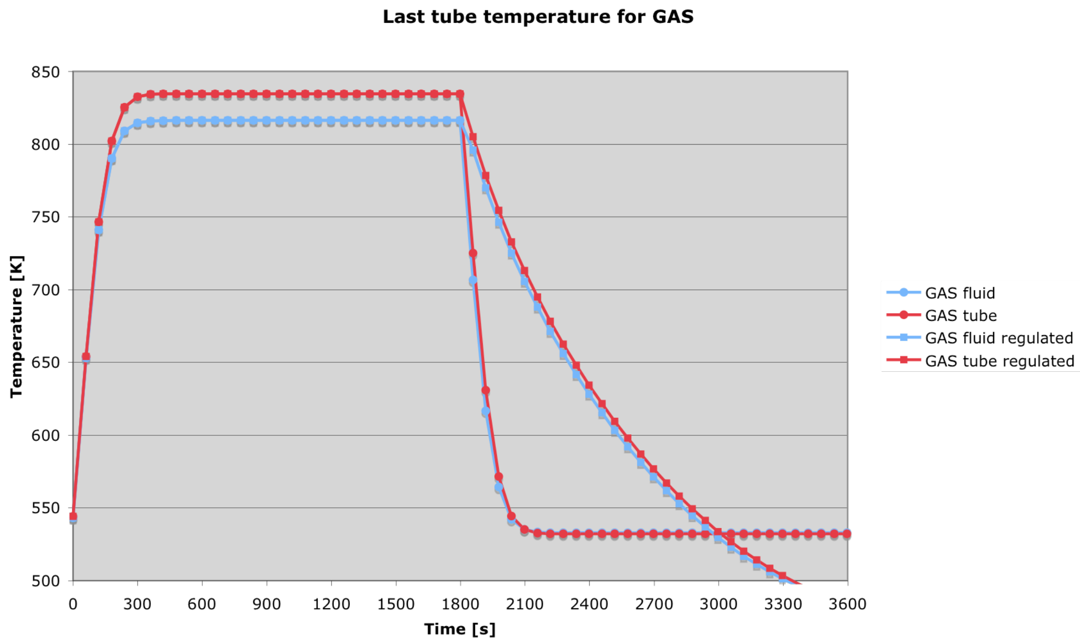

Figure 6 Fluid and steel temperature variation in the last tube for the salt system, with and without the change in mass flow rate

The transient duration is greatly increased for both systems.

It is interesting to notice in the gas that the steady state temperature is lower when the mass flow rate is reduced. In the steady state conditions in fact there is a balance between the heat loss due to irradiation and the enthalpy loss of the fluid (the inlet temperature is higher than the ambient and the outlet temperature), the higher the mass flow the higher the enthalpy flow at the inlet.

The same would happen in long times for the salt system, here it is interesting to notice the inversion between the fluid and steel temperature: when the solar irradiation is null, the steel temperature is higher than the fluid temperature for a non regulated system, while for the controlled system the fluid temperature is higher than the steel temperature.

This is clearly related to the high value of the salt heat capacity.

5. Conclusions

The transient behavior of the trough line is determined by the thermal properties of both the tube and the heat transfer fluid. The low density of the gas when compared to the salt and the oil, determines a lower heat capacity of the system and faster transients.
The rate of temperature change in time for a gas system is five times that of a salt based system and more than three times the rate of an oil system, if the same tube is adopted. The transient of the system has therefore the same order of magnitude; moreover lower rates may be obtained increasing the tube thickness.
A fast transient demands necessarily a faster control system, but also allows following better the sun irradiation fluctuations over time.