

Sim_PCS description – rev. 0.0

Massimo Falchetta – ENEA

1 Introduction

The dynamic model of the PCS circuit has been developed in the frame of the Task 4 – Work Package 12 of the Sfera project.

Indeed such model is part of the deliverables of the project. The actual release will be eventually followed by further releases as soon as they become available.

2 The PCS circuit

The PCS circuit is an experimental loop developed and operated by ENEA at its research centre of Casaccia, near Rome [1].

The test loop has been built in 2003 and begun operation in 2004. The purpose is to test (in real conditions) parabolic trough collectors and connected circuit elements employing molten salt as Heat Transfer Fluid (HTF) at temperatures ranging from 290 to 550 °C.

By means of the PCS circuit all the components (receivers, mirrors, flex hoses, process items, instrumentation ...) developed by ENEA and most of the items developed by the Italian manufacturers in the CSP field have been tested.

The plant and its basic circuit lay-out are illustrated in figures 1 to 3.

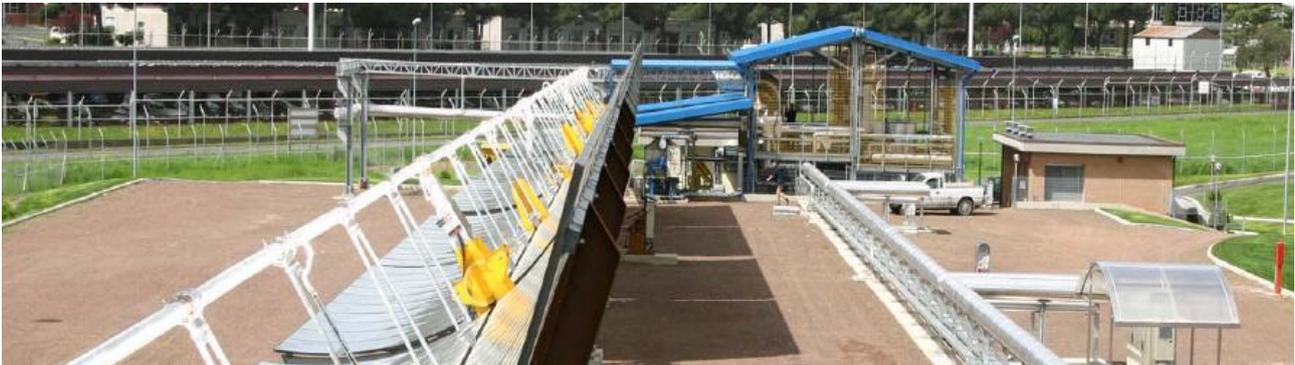


Fig. 1 – picture of PCS plant – taken from [2]

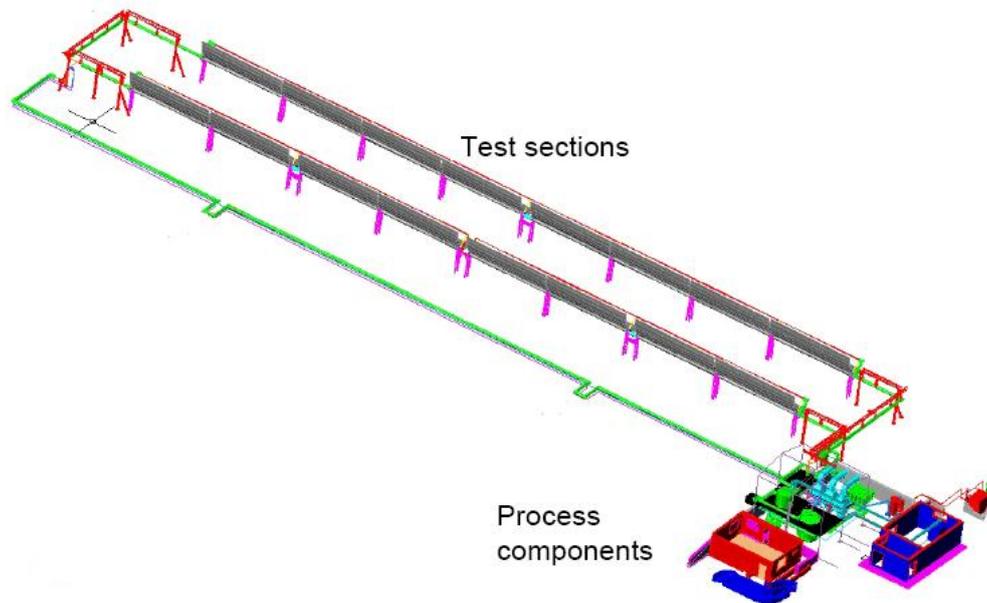


Fig. 2 – CAD scheme of the PCS circuit – taken from [1]

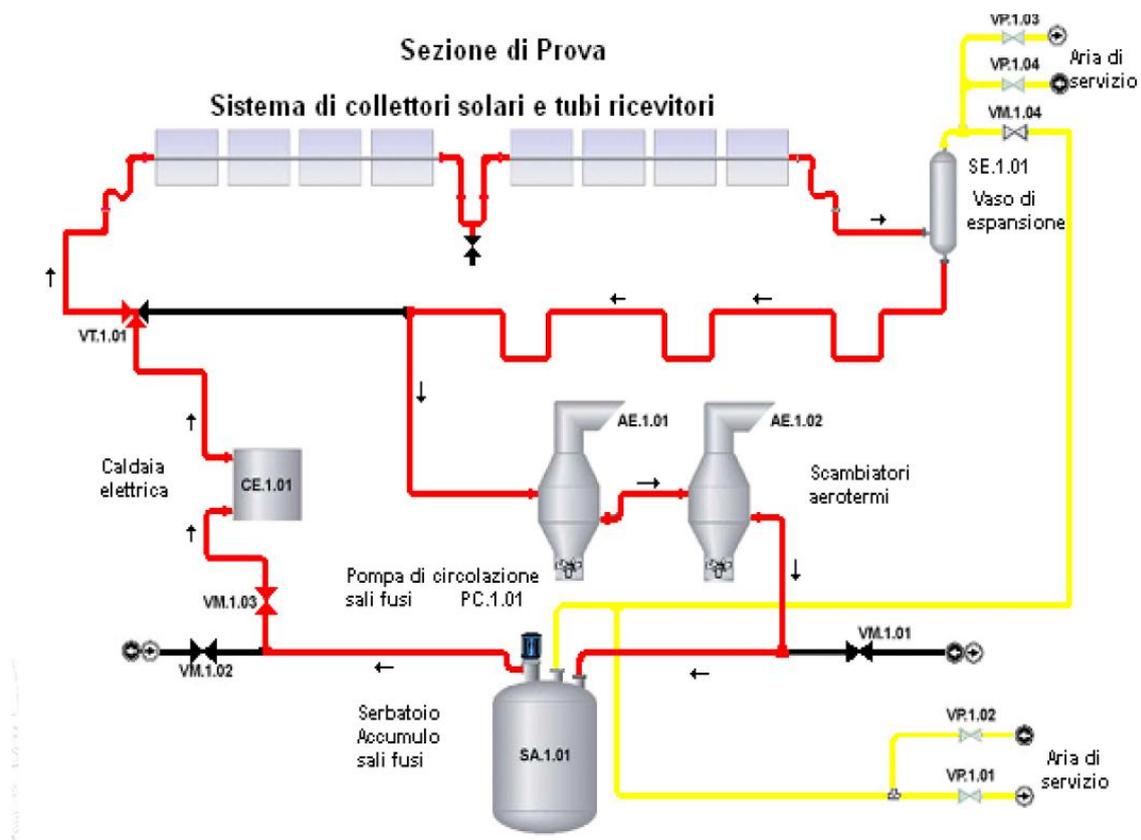


Fig. 3 – PCS basic process diagram. red: HTF; yellow. service air – taken from [2]

The HTF path (in red in fig. 3) starts from a **Storage Tank** (SA.1.01) of 9.5 m³ capacity, from which the salts are pumped by means of a centrifugal circulation **pump** (PC.1.01) rated at 18 m³/h of salt@2900 r.p.m.

Such pump has an impeller connected to the electric motor by means of a vertical shaft, thus permitting to position the electric motor in a relatively cold position on the top of the Tank.

The storage Tank is thermally insulated and equipped with electric heaters for long time temperature keeping (e.g. during night).

The electric motor is fed by an inverter, thus permitting to modulate the pump speed in order to control the HTF mass flow. The pump speed can be controlled in the 1200 – 2450 r.p.m. range; the pump is normally operated at 6.2 kg/s @ 1915 r.p.m.

In series to the pump a **regulation valve** (VM.1.03) is provided, able to further regulate the mass flow and adapt the circuit to the pump H/Q curve, if needed.

An **electric heater** (CE.1.01) follows, able to supply up to 600 kW of heat to the salt; it is actually made-up by a 33 meter - 2" steel pipe wound around in a cylindrical fashion; such pipe is supplied by a high-amp low voltage power supply, that directly injects power by joule losses due to the pipe electrical resistance.

Such electric heater is used in order to rapidly heat up the circuit if needed and/or simulate the presence of other collectors in series, in front of the collectors under test.

The HFT is then sent to the **collectors line** (Sezione di prova); 2 individual collectors in series, each of nominal 50 meters length, are provided and are the main objective of the test activities.

These collectors were manufactured by former SIFA (now D.D. s.r.l.) in a first stage; now a COMES version is installed. The actual collectors are equipped with Ronda mirrors and ASE (Archimede Solar Energy) receivers.

The receivers are heat traced by means of Joule effect power supplies similarly to the electric heater.

At the outlet of the collectors line a **pressurized vessel** (SE.1.01) is installed; such vessel has several tasks, among them to provide compliance in case of overpressures and permit to easily extract molten salt samples.

The presence of the vessel significantly influences the dynamic behaviour of the circuit, and therefore has been included also in the model.

A long **return pipe** follows, that transfers the HTF back to the Storage Tank. As others piping items, it is thermally insulated and heat traced by means of MgO insulated cables.

Before to be sent back to the Storage Tank the HTF is cooled, if needed, by means of a **fan cooler** composed by two units (AE.1.01 and AE.1.02). Each unit has a bank of 2" fin equipped pipe radiator that cools the HTF by either natural or forced air flow circulation, as needed. The total heat extraction potential of the fan cooler is in the range of 450 KW. To prevent from possible freeze, also the cooler piping can be heated, if needed, by means of direct current injection using low voltage-high amp power supplies.

All the piping connections are made with 2" stainless steel tubes, insulated by ceramic fiber and rockwool layers and heat traced by MgO insulated electric cables.

When tests are not running (e.g.: during night time) all the salts are contained in the Storage Tank, where they are kept warm (at temperatures higher than 270 °C) by means of the Tank heat trace systems.

When an experimental activity is initiated the circulation pump fills the circuit in roughly 4 minutes, and subsequently operates it according to the test needs.

When the tests are concluded, the pump is stopped and the circuit empties by gravity, restoring all the salts to the tank.

In order to easily empty the circuit, proper quotes and piping slopes have been introduced; from this point of view the vessel is the highest item in the circuit.

Such quotes and slopes have been represented properly in the simulation.

Note 1: Filling and emptying operations are not represented by the SIM_PCS model; therefore the model represents the normal operation of the circuit during tests.

3 The SIM_PCS model

The SIM_PCS model simulates the main aspects of the PCS plant from the point of view of its dynamic behaviour,

It is a quite accurate model in order to predict actual plant's behaviour as subject to operator's maneuvers, either in real-time and in accelerated time (up to 100x, depending on model size and computer speed); in other words to investigate the process control aspects and to give a support for plant's operation. On the other hand, it is of course not the best model in order to evaluate a year-round plant's performance, due to the quite long execution time that would be needed.

The SIM_PCS model has been developed ad-hoc for the purpose of Task4-WP12 of SFERA, building upon ENEA knowledge of the PCS circuit and former models developed in Simulink modelling environment of MATLAB package [3].

The Simulink environment is very useful for process control and dynamic simulation investigations, but problems arose when trying to deploy an "executable" version – able to be executed outside the Simulink environment – for the purpose of SFERA general users.

3.1 The Isaac Dynamics environment

Isaac Dynamics is a modelling environment developed by Struttura Informatica [4], that recently devoted to the simulation of CSP systems, starting from its previous know-how on simulation of thermal power plants.

Such effort on CSP is performed in collaboration with ENEA.

Indeed, the adoption of Isaac Dynamics was quite useful in order to transfer the Simulink models to a more practical and, most important in the specific case of Sfera, deployable environment.

Isaac Dynamics has also intrinsic advantages from the point of view of real-time simulation and interaction with the model, allowing to change the simulation speed on line (from real-time to 10x or more), pause-restart the simulation, save the variable state in order to store new initial states, and so on.

After accurately modelling a plant in the Isaac Dynamics environment, you can run a simulation quite close to a "simulated experimental activity". Indeed to find a reasonable initial state is one of the most delicate tasks in the case of such type of models. But once the model runs, you can reach a reasonable steady state condition that you can save as new "initial state" for further "experiments" in different conditions, saving a lot of time.

3.2 Lay-out of SIM_PCS

The lay-out of the SIM_PCS circuit is shown in fig. 4.

As in the real circuit the flow, following a clockwise pattern, starts from the Storage Tank (Tank); such Tank is maintained at atmospheric pressure by means of an exhaust valve (VENT).

Through a pump (PUMP) the flow is sent to the electric heater (HEATER); a valve (VALVE) allows to further control the flow.

The heater control block (HEATER_CONTROL) permits to operate the heater either if its temperature falls belows 270 °C (heat-tracing action) or if additional power is needed; such action is controlled by the block HEATER_RAT (0 – 100%).

The short pipe element (outlet_pipe) is introduced to represent the riser pipe from the impeller to the Tank outlet, actually producing a vertical increase of quote of 3.5 m; the round elements (M0 ... M6) are “manifolds” introduced in order to permit equation connection.

The heater feeds a thermally insulated and heat-traced pipe – 25 m. long – (IN_PIPE); the heat tracing equipment is represented by the block HeatTracePowerSupply, that feeds power to the pipe if its wall temperature falls below 270 °C; the block INS_1 represents the thermal insulation of the pipe.

The receivers follow (REC1 and REC2); both are heat-traced by Joule effect and exchange thermal power with the external environment (according to the receiver thermal characteristics) while receiving power from the sun through the collector’s mirrors (COL_1 and COL_2).

In turn, the mirrors receive solar power from the sun, according to the DNI value, incidence angle and tracking error, if any, focusing part of it to the receivers, according to the optical characteristics of the mirrors.

Again through a short pipe element (pipe0), the flow enters in the pressurized vessel (VESSEL), then through a quite long insulated and heat-traced pipe (OUT_PIPE) is sent to the fan cooler unit (COOLER); the heat transfer characteristics are controlled by the block FAN_RATE (0 – 100%).

A small descending pipe (pipe1) completes the circuit to the Storage Tank.

INPUT					
Model	Block	Variable	Description	Value	Dim
FCS_completo	PUMP_rpm	X0	VARIABLE X0	1515.0000	Adimensional
FCS_completo	VALVE_LIFT	INVAL	INPUT VARIABLE	1.0000	p.u.
FCS_completo	error_1	X0	VARIABLE X0	0.0000	rad
FCS_completo	error_2	X0	VARIABLE X0	0.0000	rad
FCS_completo	HEATER_RAT	INVAL	INPUT VARIABLE	0.0000	Adimensional
FCS_completo	FAN_RATE	INVAL	INPUT VARIABLE	0.0000	Adimensional
FCS_completo	INPUT_DNI	INVAL	INPUT VARIABLE	900.0000	W/m ²

Initial condition: 290 °C - 6.2 kg/s

PCS model - rev. 0 - 28/02/2012
 Developer: Massimo Falchetta - ENEA
 Platform: Isaac Dynamics 2.2 by Struttura Informatica - Italy

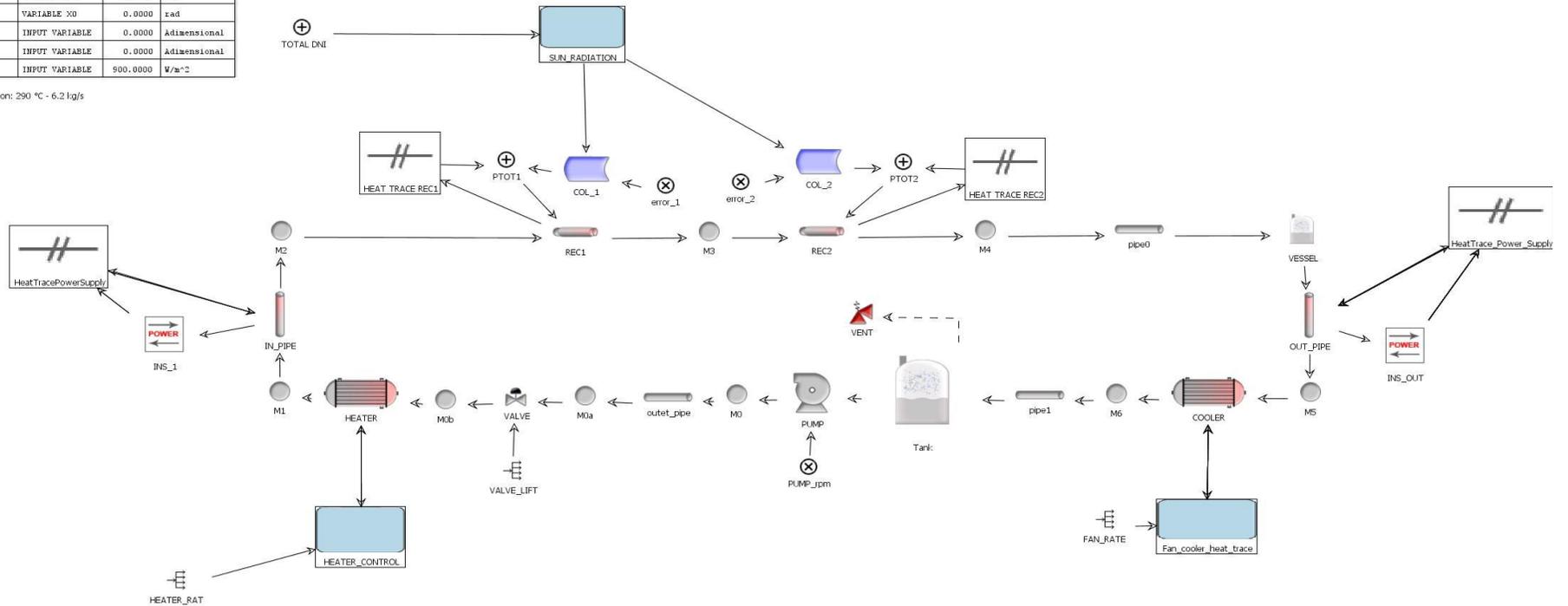


Fig. 3 – Layout of SIM_PCS

4 Using SIM_PCS

4.1 Installation

After extracting the SIM_PCS.zip file the following directories should appear under the SIM_PCS root:

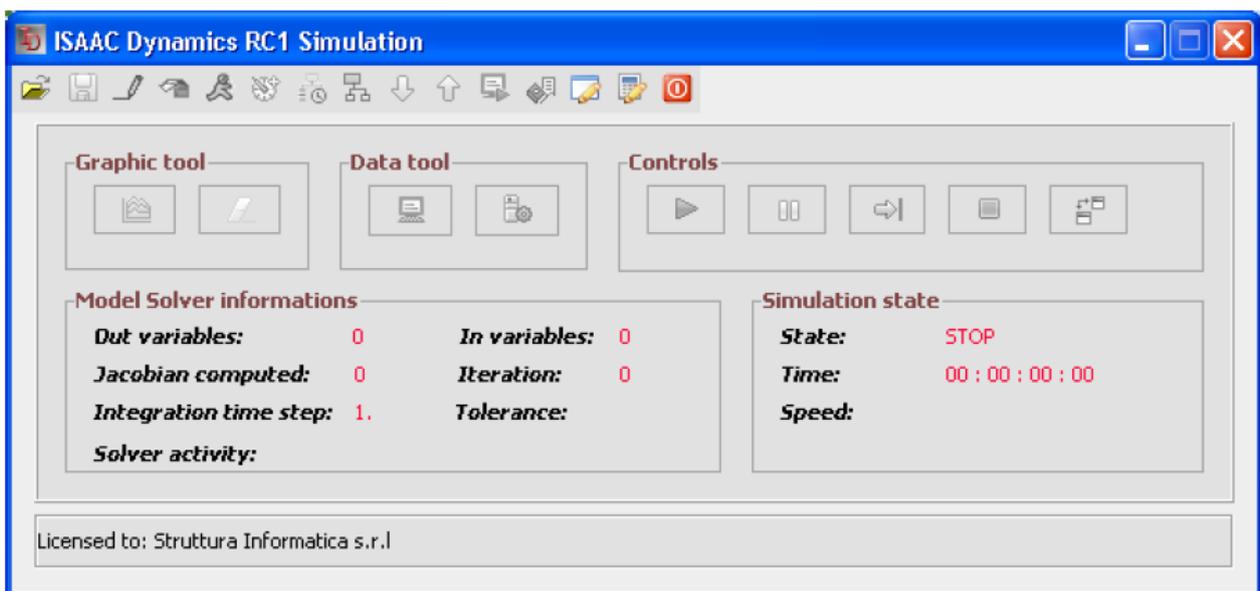
- Bin
- Icons
- Jre1.6.0_07
- lib
- library
- work
- xml

These directories have been created by the Builder Interface environment, that of course is not included since it is part of the commercial package, since it permits to create new models. In any case the simulation environment is exactly that of the actual commercial package, and in principle allows to operate the model in the same way.

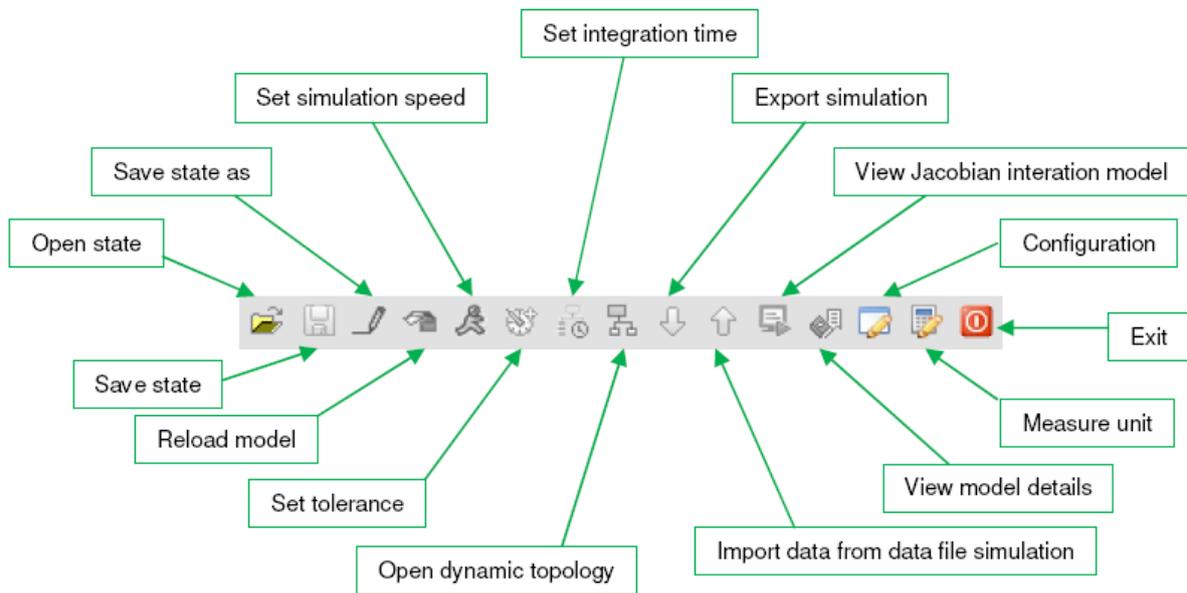
4.1 Start-up and first trial

To start the model just double-click on the icon “ModelinterfaceStart” that appears under the SIM_PCS root.

After a number of seconds (depending on your platform, typ. 10 sec.) the main Isaac Dynamics Simulation window will appear (actual window can be slightly different, due to recent release improvements).

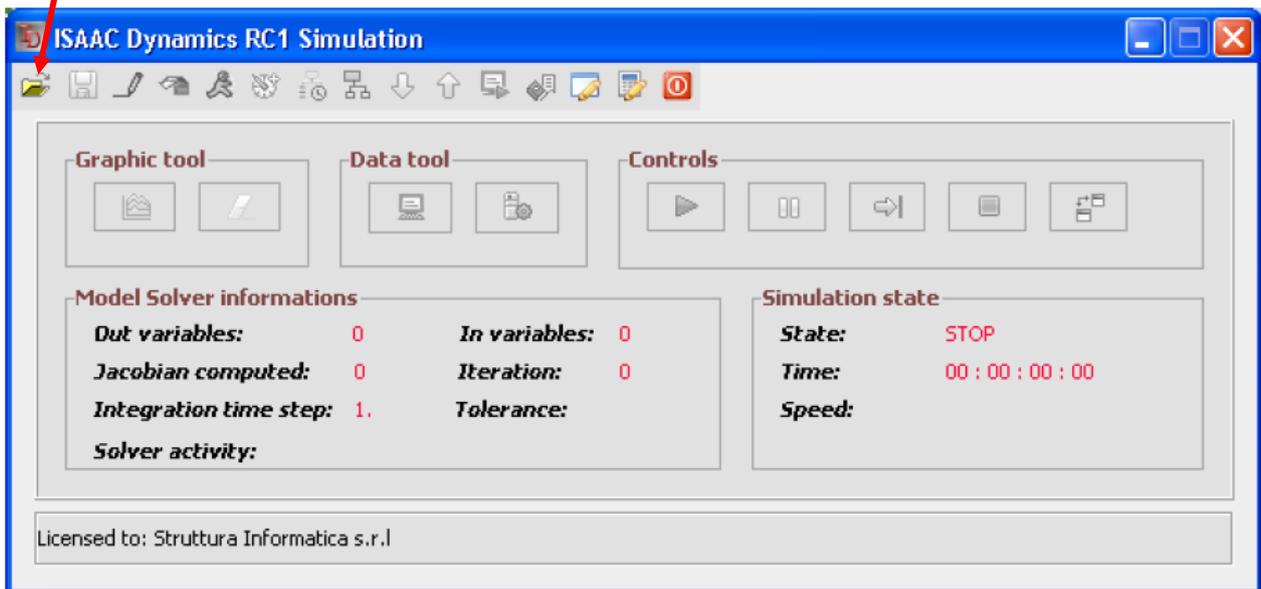


The meaning of commands enclosed in the Top toolbar is as follows

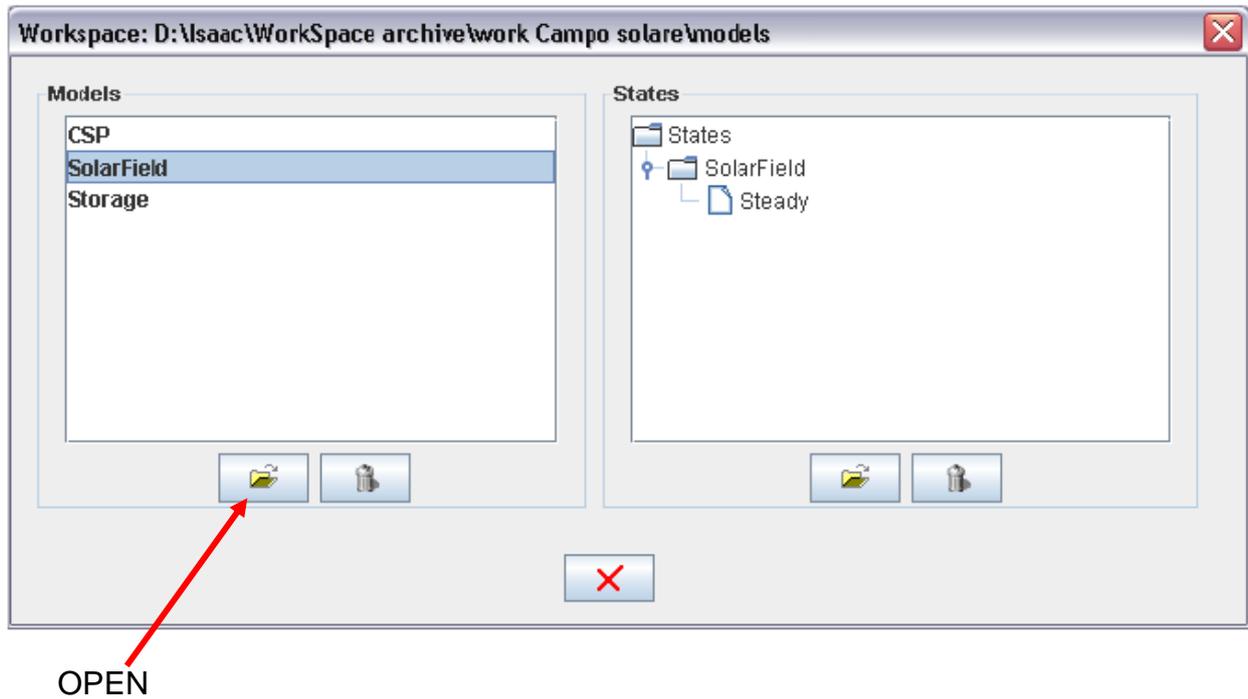


Click on the open symbol at extreme left on the Top toolbar

OPEN



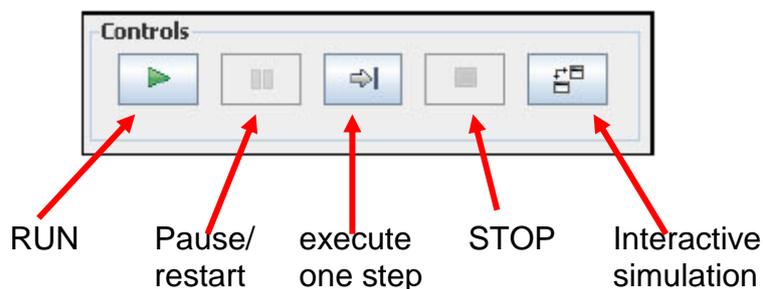
A window similar to the following will appear. In your case the name “PCS_completo” will appear on the left side.



So, open the model “PCS_completo”, by clicking on it and subsequently on the “open” symbol at the bottom (of course, don’t click on the “garbage bin” symbol, otherwise you delete the model.).

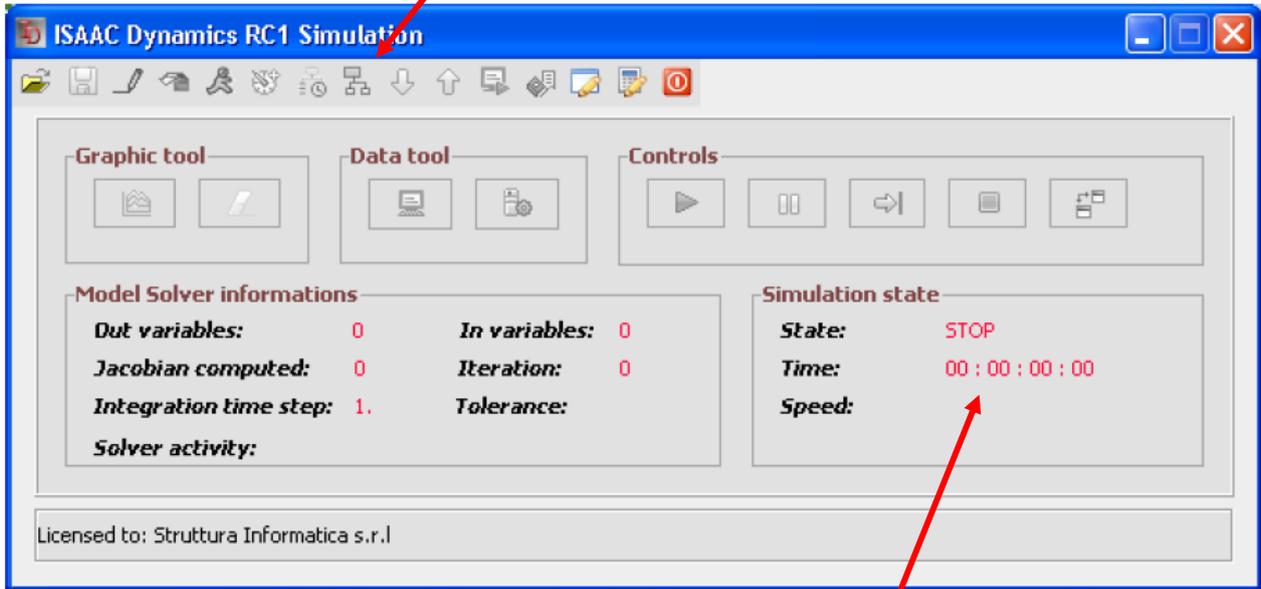
On the right side, also an initial state 290 C is stored, just in case you will save a different initial state after executing the simulation, and you want to restart from the 290 C initial condition. Indeed this state corresponds to the pump running at 1915 r.p.m. and roughly 290 °C all around the circuit.

Once the model is loaded, you can run it just clicking on the green arrow under “Controls”.



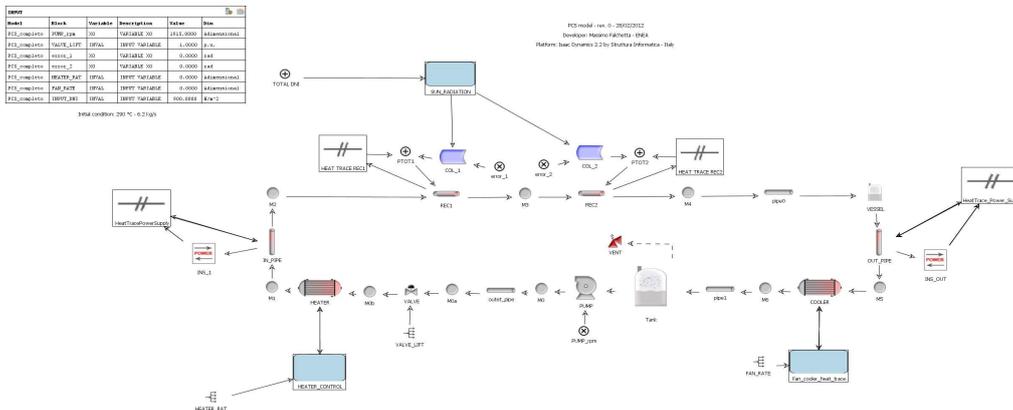
The Time will begin to run, but of course you don’t see anything else of really interesting. This simply means that the program is running correctly. So, after some seconds, just stop the execution, by clicking the pause icon, just near the start icon. Now, on the Top toolbar, just click on the 8th icon from left; this opens the model dynamic topology, that is exactly as that of the model builder used to build the model, but with the advantage of allowing to observe all the states evolution during execution.

Open the dynamic model viewer



The time should run at the correct rate in non-problematic calculation cases

The dynamic model viewer will show the lay-out of the plant; in addition it will permit to interact with the plant blocks.



Just enlarge the dimensions as needed, than you can inspect the variable values on each block (Input, Outputs, geometrical parameters) just clicking on each block. Now, you focus on the INPUT table (fig. 4), that contains the “major” input variables that a plant’s operator should control (it will be described later). You can click on the “graphics” (top right) icon of The INPUT table. This opens a graphic windows that will permit to observe the trend of the Inputs. The window will be similar to that shown in fig. 5, that explains how the graphic output appears.

variations icon graphics icon

INPUT					
Model	Block	Variable	Description	Value	Dim
PCS_completo	PUMP_rpm	X0	VARIABLE X0	1915.0000	Adimensional
PCS_completo	VALVE_LIFT	INVAL	INPUT VARIABLE	1.0000	p.u.
PCS_completo	error_1	X0	VARIABLE X0	0.0000	rad
PCS_completo	error_2	X0	VARIABLE X0	0.0000	rad
PCS_completo	HEATER_RAT	INVAL	INPUT VARIABLE	0.0000	Adimensional
PCS_completo	FAN_RATE	INVAL	INPUT VARIABLE	0.0000	Adimensional
PCS_completo	INPUT_DNI	INVAL	INPUT VARIABLE	900.0000	W/m^2

Fig. 4 - The INPUT Table

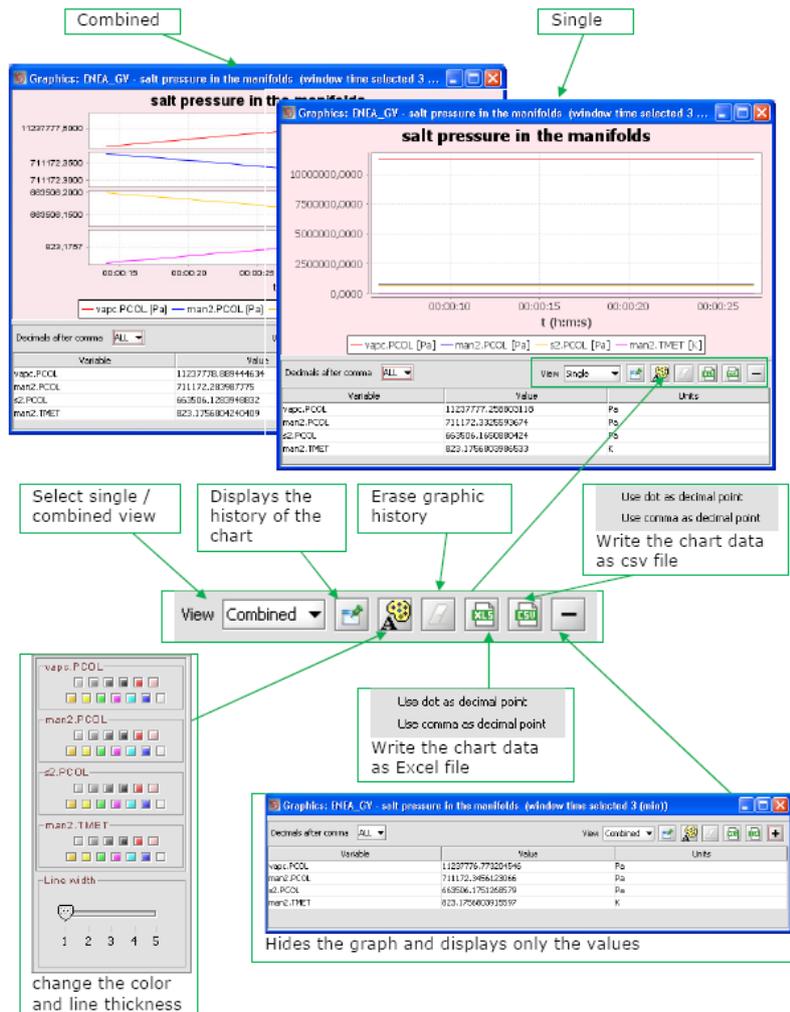


Fig. 5 – general appearance of the graphic window in Isaac Dynamics

Correctly re-size the window, then click on the other icon of the INPUT table; this action will open a “PCS_completo_Variations” table similar to that shown in fig. 6, that allows you to easily vary the inputs data during run.

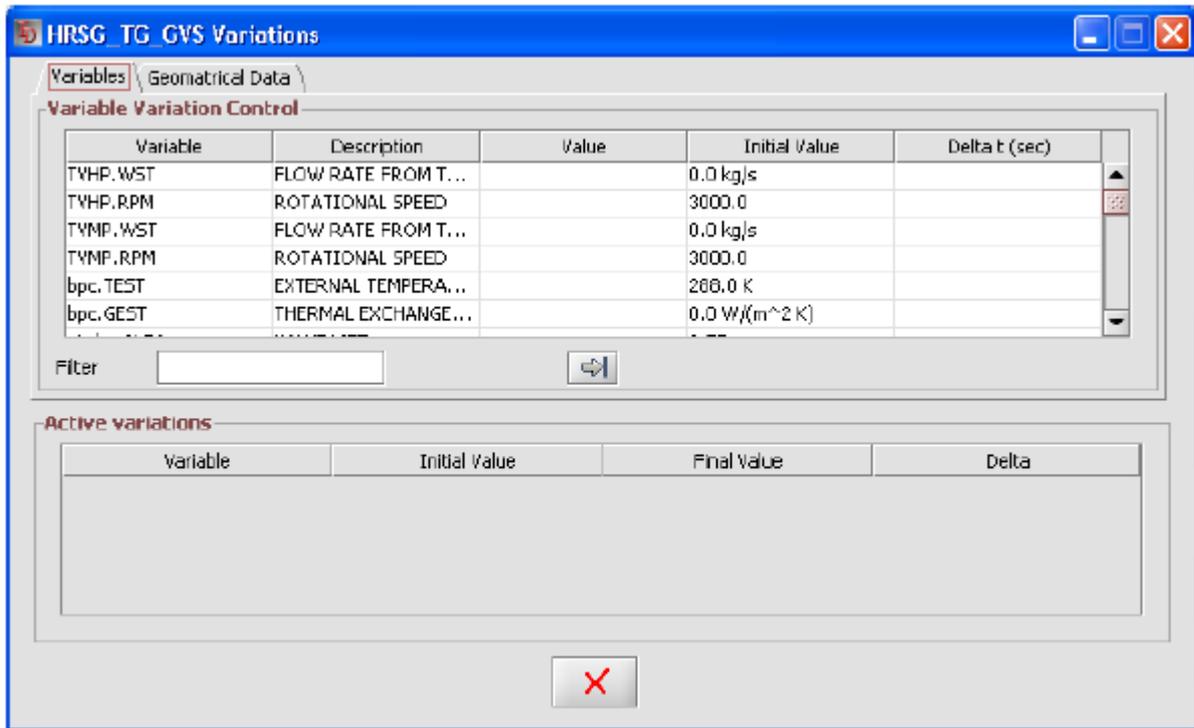
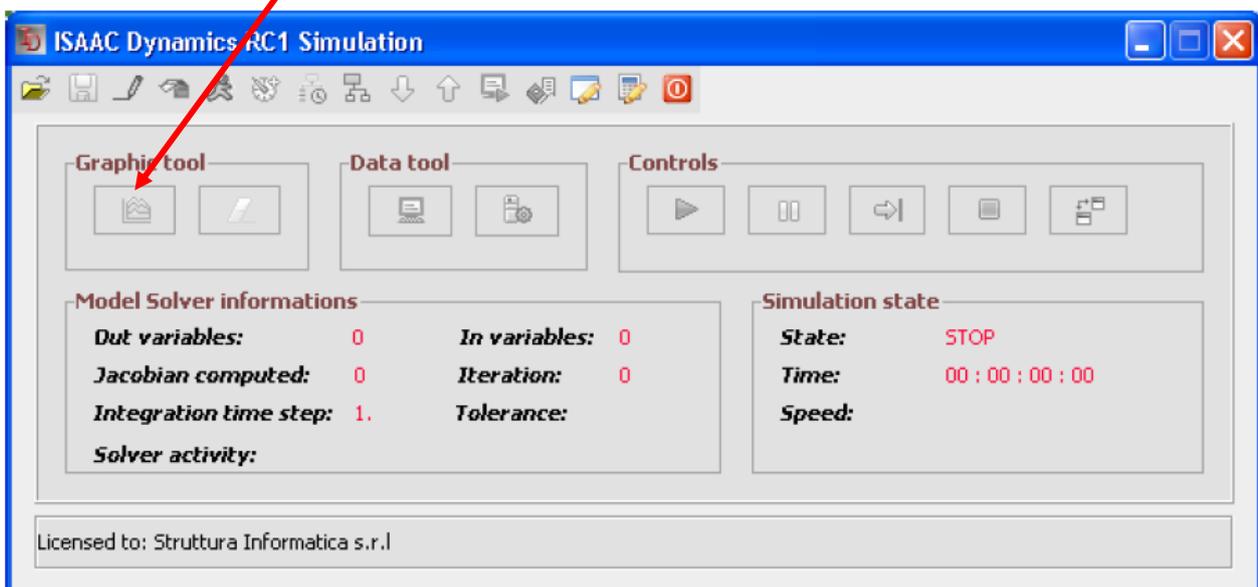


Fig. 6 – general appearance of the variations window in Isaac Dynamics.

In the case of SIM_PCS INPUT table only variables, not geometrical data, can be varied.

Note2 : if you want to change the geometrical data, you should act at the level of individual blocks.

Finally, click on the graphic icon that appears on “Graphic tool” of the main Simulation window.



A “PCS_completo Graph Selection” window will appear, similar to that shown in fig. 7; you can load one of the pre-set graph, or prepare a graph with the variables you like.

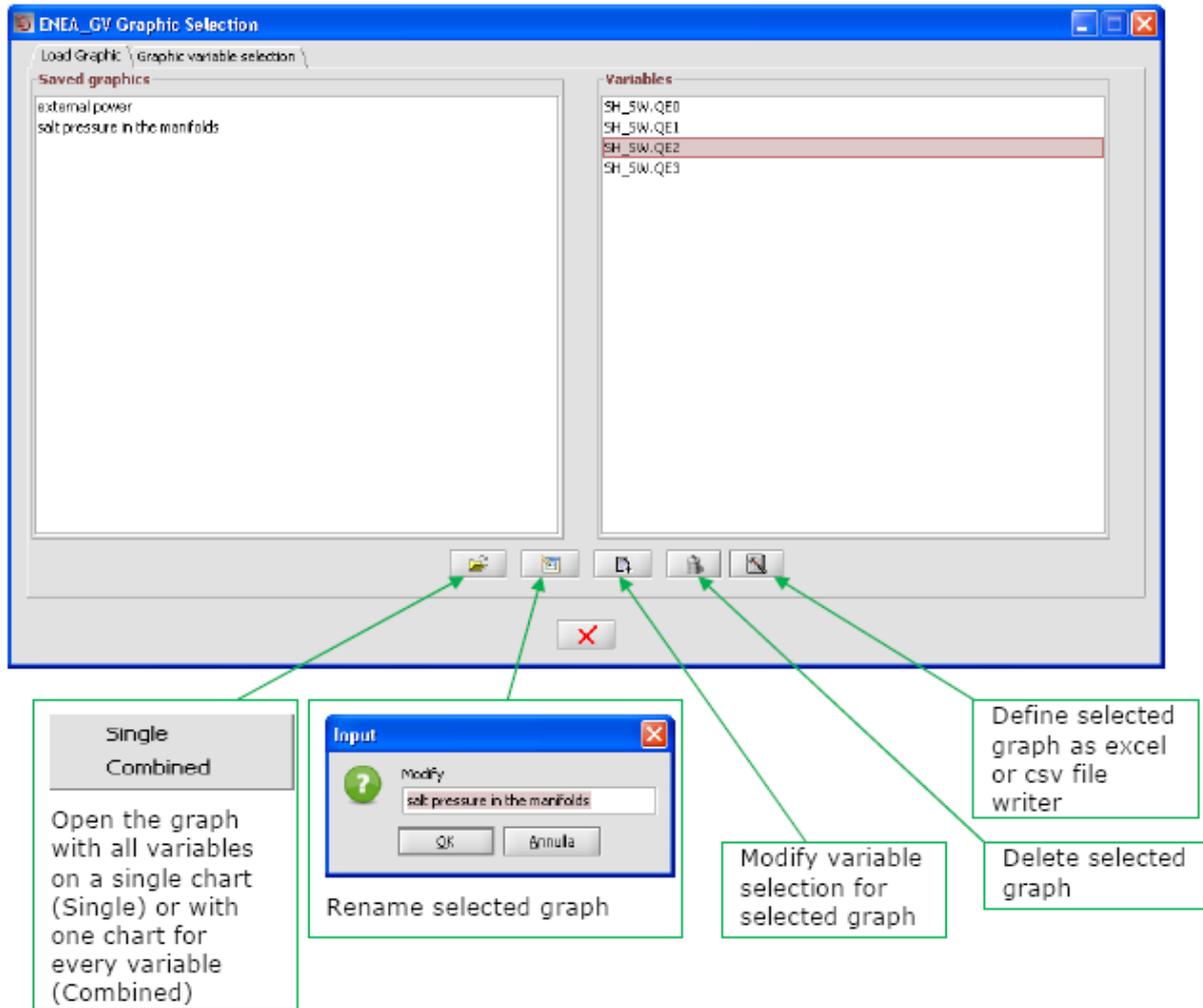


Fig. 7 – general appearance of the graphics selection window in Isaac Dynamics

Just open the graph “Outputs” as a first choice, clicking on it, then clicking on the “open” symbol that appears on the bottom; choose “combined” in order to see the traces in different axis.

Re-size the graphic window as you need.

>>>>>>>>>>

Now you should have typically 6 Isaac windows active: the main simulation window; two graphic windows (Inputs and Outputs); the dynamic model viewer; the Graph selection window (that you can eventually close for now); and the “variations” window.

Now, you can resume the simulation, just clicking on the re-start icon (formerly the pause icon, now has the form of a sandglass); as the model resumes and keep running again, looking at the graphs you can observe the evolution.

If you have not done mistakes in the meantime, the simulation will resume gently. You will probably not understand very much at the beginning, as instead you will after reasoning a little more on the plant’s dynamics. To do so, just pause the simulation and observe the dynamic model interface.

Indeed, during execution you can pause and re-start the model (second icon of “Controls” panel); execute a single step (third icon); stop the execution (fourth icon); better don't try other actions for the moment.

You can also increment/decrement execution speed (real-time; 2 .. 10X; maximum speed) just clicking on the 5th icon from left (an orange guy running) on the Top Toolbar.

4.2 Observing the behaviour

What you have been doing up-to now is just to observe a sort of “natural evolution” of the system as subject to the fixed input values; in fact, the INPUT graph window shows 6 perfectly horizontal lines: nothing really interesting (If not, it probably means you have done something strange for your own).

Pause the program and reflect. First of all, you should observe how the resolution of numbers is high, probably too much for an engineer's eye; so, reduce the decimals after comma at two or three, in the graphic windows.

Then, reflect as the OUTPUT graphs appear as slowly evolving curves; but if you look at the numbers, the variation is very limited, because the plant is practically in an “almost steady-state” situation.

Now you can begin to play a little more with the inputs.

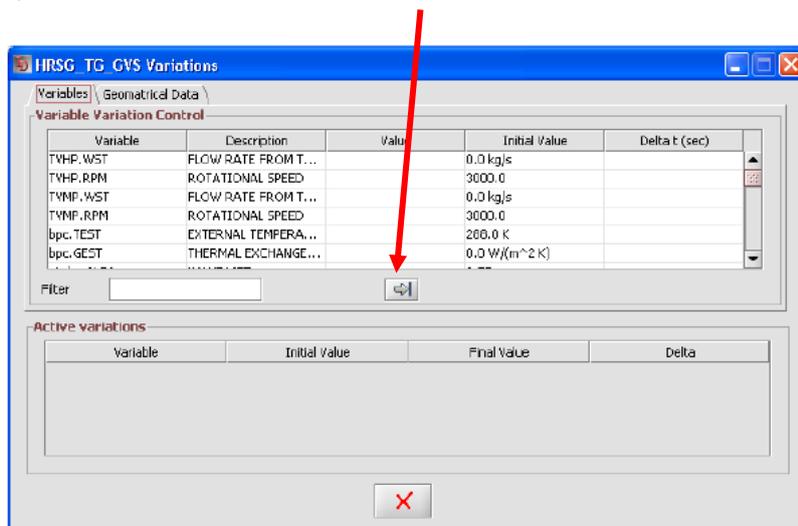
4.3 Change the inputs

In order to change the inputs you have two choices;

- 1 act through the PCS_completo Variations window; here the nominal input parameters that a normal PCS operator will control are included
- 2 Right-Click on any block of the “Dynamic model viewer”, than click on “open blocks variation”; this action will permit to vary, on line, any input data or geometrical parameter of the selected block.

The second way is up-to you but it is not recommended as initial choice, since only an expert technician would do the same on a real plant.

So, open the PCS_completo Variations window; it is better to operate on it while the program is in pause; now you can watch the actual value of the input variables (third column); you can input a new variable to be targeted (fourth column); and a deltaT in seconds for the operation; then click on the arrow;



this action will produce a new line, with the variation (or variations) that will take place immediately or as the program will start-again; in other words, the actual input variable will be linearly led to the target value in the deltaT time (just as performed when operating on a real plant from it's DCS or SCADA HMI).

Please, input reasonable values and reasonable maneuvering times, otherwise the program could crash, exactly as could happen if you suddenly close a valve operating at full flow without any built-in safeguard in the valve actuation time; indeed in this case you can easily create a high pressure that will provoke a rupture disk intervention or even a pipe breakage. The advantage of simulation is that you cannot produce major damages with such type of actions.

For example, set the pump speed to jump to 2450 r.p.m. in 10seconds.

At re-start, you will observe a more interesting evolution of mass flow, vessel level, etc.

May be it will be not particularly exciting, but that is all.

In any case the PCS circuit is a quite calm, long term evolution system and you should never experience, at least for normal computing states, fast and strange transients as you can experience with e.g. aircraft or electric drive simulation or so on. So, don't expect very fast dynamics.

4.4 Inputs description

The inputs allocated to the input table are:

- 1 Pump_rpm: the pump speed in r.p.m. Nominal speed is 1915 r.p.m, that roughly yields 6.2 kg/s of HTF mass flow; operative range of the pump is within 1200 and 2450 r.p.m.; reducing too much (below 1000 r.p.m., just try) the speed will (in the real plant) produce pump vibrations due to the long shaft critic speed (obviously not represented); but it will also empty the pressurized vessel (a real behaviour); in this case the collector would operate with a partial void in the last part of the receiver, therefore it is not a safe plant operation. In turn such situation will stop the program as the level is below zero, due to computational discrepancy. That means that the model works correctly !
- 2 Valve_lift: this is the valve lift, or opening rate (0: valve closed; 1: valve full open); normal operation is with valve lift from 0.5 to 1. Again a too closed valve will provoke an emptying of the vessel with the aforementioned problems.
- 3 error_1: the tracking error of collector 1. Such error is actually measured and input in mrad (don't care of the "rad" value of the table). Nominal error is zero (perfect tracking). A 20 mrad error (a little more than 1°) actually leads to zero the solar radiation focused onto the receiver.
- 4 error_2: the same as error_1, for collector 2.
- 5 HEATER_RAT: rate of heater power, from 0 to100%. 100% corresponds to roughly 600 kW.
- 6 FAN_RATE: exchange coefficient produced by the forced ventilation of the cooler. Such rate is expressed in percent of the full rate forced ventilation exchange coefficient. At 100% rate the cooler will exhaust around 450 kW of heat to the cooling air. In any case, an exact model of the fan-cooler, linking the fan speed to the heat extraction, is not provided since it is not necessary for basic controlling purposes (of course it can be developed if needed). It is therefore assumed that the operator acts by means of a precalculated non-linear table.

- 7 INPUT_DNI: the value of DNI (Direct Normal Irradiation) that is freely input by the simulation operator (not the real plant's operator, that will have to patiently rely upon Phoebus will). The solar input needs a further clarification as follows.

4.5 Solar Input

In SIM_PCS, the solar input is composed by three sources:

- The “calculated DNI”; such DNI is calculated by the “SUN1” block of Isaac Dynamics set of blocks. A SUN1 block is actually embedded in the SUN_RADIATION module; using the Yang model ([5]), SUN1 calculates a typical DNI on “clear sky conditions” according to the geographical position of the site and the time of the year.
- The “measured DNI” taken from an experimental data set; actually an experimental data set of measured DNI taken at the PCS site is provided, sampled at 5 sec. sampling time. Such file starts at 8 a.m. and stops at 6.30 p.m.
- The “Input DNI”; such input can be freely chosen by the simulator operator. Preset value is 900 W/m²

These three inputs are combined in order to form the “Total DNI” value that is actually sent as input to the collectors.

The block “TOTAL DNI”¹ actually mixes the three inputs through three coefficients C0, C1, C2, whose value should be either 0 or 1. In order to set the coefficient value, just right-click on the “TOTAL DNI” block, then on “open block variation”, to open its parameters; choose “geom” (geometrical parameters), and set the values.

Examples:

- C0=0; C1=0; C2=1 (preset values); in this case the DNI value is directly controlled by the user, i.e. Total_DNI=INPUT_DNI
- C0=0; C1=1; C2=0; in this case the DNI is taken from the stored dataset (from 8 a.m. to 6.30 p.m.)
- C0=1; C1=0; C2=1; in this case the DNI is taken from the calculated “clear sky” DNI, plus a “disturbance” that can be input by the user.

Note 3: the SUN_RADIATION module calculates the Aperture Normal Irradiation (ANI) that irradiates the mirrors surface, taking into account the incidence angle (in turn calculated by the SUN_RADIATION module on the basis of time of the year, geographical position, collector orientation ...).

This is the final irradiation flux sent to the collector mirror area. Incidence Angle Modifier is actually not taken into account in the present version.

¹ Apart from the parameter values, the SOLAR_RADIATION block will anyway limit the final DNI value in the range 0 -1050 W/m²

Further hints

The SIM_PCS model is composed by blocks and macroblocks (collections of blocks). For example, REC1 is a standard block, while HEAT_TRACE_REC1 is a macroblock embedding a number of elementary standard blocks. The complexity (number of parameters/equations) is not directly linked to the quality of the blocks (Block or Macroblock). Macroblocks are used here just for graphical purposes.

If you want to see the structure inside the macroblocks, just right-click on the model dynamic topology window area, then select “Macroblocks” and toggle the “implode/explode macroblocks”.

Note 4: please note that actually the “solar time” starts at 8 a.m. of first of January. In order to change the “solar time” you should wait for the simulation going on. As an alternative, you should “explode” the block SUN_RADIATION, then change the Initial time in the block Time (in seconds), then save the initial state and restart the model; of course you will get longer day duration (e.g. in June), but you will not be able to read the data set, since after 6.30 p.m. of 1st of January the data output will be zero.

The actual 0.0 version will be improved (e.g. with new improved DNI data-sets) as possible with new releases of SIM_PCS. In case of questions, suggestions, comments, please mail to: massimo.falchetta@enea.it

References

- [1] http://www.nrel.gov/csp/troughnet/pdfs/enea_activities.pdf
- [2] http://www.gedeon.prd.fr/ATELIERS/27_28_novembre_2006/exposes/Molten_salts_fabrizi.pdf
- [3] M. Falchetta, P. Di Ascenzi, C. Manfredi, I. Vaja, D. Scatolini – Messa a punto e pre-validazione della modellistica termofluidodinamica dei componenti solari tramite confronto con i dati sperimentali PCS – ENEA internal report SOL/RS/2004/20 – 2004.
- [4] <http://www.strutturainformatica.it/>
- [5] Yang model - contact Struttura Informatica for details.