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Modeling of solar district heating: a comparison between TRNSYS and MODELICA

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Summary

In order to optimize their design, operation and control strategies, Solar District Heating (SDH) require thermalhydraulics simulations capabilities. In this paper, we present how SDH components and system models can be build both with the TRNSYS energy simulation program and the equation-based MODELICA simulation language. Therefore, three SDH components (pipe, substation and solar collector), a production plant and a recently built SDH network are modeled and simulated using TRNSYS and the Modelica/Dymola tool. The simulations performed show that both approaches yield similar results when comparable modeling details are considered in the software. However, the Modelica language has native multi-physics simulation capabilities. For instance, robust and publicly available solutions exist to account for hydraulics phenomena with the Modelica solution. On the other hand, extending the simulation scope of TRNYS to include hydraulics would be a very time-consuming task. On a general basis, it can be said that development costs are lower and modeling possibilities are wider for the Modelica solution. This overbalances the generally higher computational cost observed with the Modelica/Dymola solution. These reasons have led our research group to select the Modelica/Dymola tool to supplement the traditional solution based on TRNSYS for simulation activities related to SDH.

1. Introduction

District Heating (DH) networks have an important role to play in the design of future sustainable energy systems. For instance, solar thermal power connected to a DH, namely a Solar District Heating (SDH), can provide renewable energy to individual customers at competitive cost. However, due to firstly the sensitivity of solar collectors to the operating temperature and secondly to the intermittence of the solar resource, SDH are generally more complex than classical District Heating. A good insight in the thermalhydraulic behavior of such networks is therefore recommended to optimize their design, their operation and the definition of their control strategy. Such insight can be brought by numerical simulation capabilities.

This paper aims at comparing TRNSYS and Modelica for SDH applications. (Elsheikh et al., 2013) and (Wetter and Haugstetter, 2006) have compared these tools but not in this domain. This paper starts with a general introduction on TRNSYS and Modelica (section 2). In section 3, the SDH case study that will serve as a comparison basis is described. Sections 4 and 5, respectively compare the modelling capabilities at the component scale (pipe, substation, solar collector) and at the system scale. The system scale analysis is based on the case study and relies on the modelling of two systems. The first system represents the production plant. Results are compared from a thermal point of view. The second system is the DH network where thermalhydraulic phenomena such as heat transportation time are at play. The last section (section 6) compares the computational costs of each tool.

2. General remarks on TRNSYS and MODELICA

TRNSYS v17.1 (SCL et al., 2012) is a software devoted to the modeling of thermal systems and the simulation of their transient behavior. A variety of component libraries suitable with the TRNSYS environment are currently available. These libraries already include models for many SDH components such as heat exchanger, heat storage, solar collector, substation etc. Several of them have been validated by

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experimental data. Recently, TRNSYS has been used to model a SDH in Canada in order to optimize its control strategy (Quintana and Kummert, 2014). For its simulation needs, our research group at CEA-INES uses the commercial TESS library (TESS, 2011) but also develops and maintains a library for specific components (e.g. solar collectors, substations,…). From a practical point of view, the development of a new component model in the TRNSYS environment requires the programmer to code (FORTRAN language) the representative mathematical equations as well as a dedicated numerical solution algorithm. Moreover, the native simulation scope of TRNSYS excludes hydraulics. This is a limiting factor when one wants to study a DH network with a loop architecture for instance. Extending the code to account for new physical phenomena would be very expensive. These reasons have led our group to take an interest in alternative modern tools with native multi-physical modeling capabilities.

Modelica is a recent acausal equation-based object-oriented programming language designed for multi-physics simulation (Fritzson, 2004). Among many advantages of such an approach, these characteristics allow maximum code reusability and natural modeling. Development costs are therefore significantly reduced. Moreover, high quality and well documented open-source Modelica libraries have been developed these past years in the thermalhydraulic domain (Elmqvist et al., 2003; Ljubijankic et al., 2009; Wetter et al., 2014). Recently, the number of research projects addressing DH modeling and relying on Modelica has significantly increased. For instance, in (Pol et al., 2011), Modelica models are used to improve the control strategy of DH systems by using the network as storage. A library, named *DistrictHeating*, is currently being developed at CEA-INES. This library includes generic components for pipes, pumps, substations, heat generators, and heat storage modeling. The Dymola simulation software (Dassault Systèmes, 2013), generally considered as the most advanced Modelica-compliant tool, is used in this study as the tool implementing the modelica language specifications (model translation, solver, pre- and post-processing …).

The Modelica/Dymola solution proposes several non-linear integration algorithms (Euler, DASSl, RADAUIIA …) with fixed but also variable integrator steps. This last feature associated with the use of implicit time marching methodology produces good overall numerical performances. On the other hand, TRNSYS uses a constant time step solver. It is generally agreed by the TRNSYS community that simulations results are considered acceptable despite the non-convergence of a low fraction of the total amount of time steps. This implies that the user must check via post-processing that mass and energy are well conserved by the numerical results.

There are important differences in the ease of use and the ergonomics between TRNSYS and Modelica/Dymola since they have not been developed during the same decades. In terms of post-processing, Modelica/Dymola offers more advanced and attractive solutions. With TRNSYS for instance, the user must select manually and prior to simulation which calculation variables to store. The time evolutions of the selected variables are dumped in text files and are then to be analyzed with another tool. On the contrary, Modelica/Dymola includes a post-processing environment: any calculation variable can be directly plotted. Color animations of any scalar field (eg. temperature, pressure …) are also possible with this tool.

3. The case study : a new SDH in Balma

3.1. The SDH network

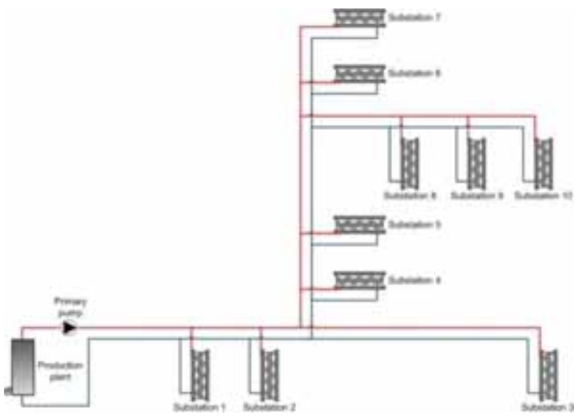

Fig. 1. Diagram of the Balma production plant

The present study is based on a new SDH built in Balma near Toulouse (south of France) in 2012. The DH network provides energy to 600 apartments through 10 sub-stations. The total annual load of the SDH is about 4200 MWh. The set point supply temperature is varying according to the season: summer (1st of October to the 15th of May), it equals 83 °C ; winter, it equals to 75 °C. Every substation is designed to operate at 80/50 °C for the primary side and 65/45 °C for the secondary side. Pipes are pre-isolated pipes made of 3 layers: the tube in galvanized steel, the insulation in PUR foam, the external layer in PEHD.

3.2. The production plant

The production plant consists of a solar plant (vacuum tube solar collectors and a solar storage tank), a heat exchanger (enabling the heat exchange between the solar plant and the DH), a biomass boiler, a gas boiler and two storage tanks. The solar collectors are connected to the DH network in series on the return pipe (cf. Fig. 2). Tab. 1 presents their parameters.

Tab. 1. Parameters of the production plant components

Component	Parameter	Value
Solar plant	S	458 m²
	η_0	0.71
	c_1	0.95 W.m^{-1}.K^{-1}
	c_2	0.005 W.m^{-1}.K^{-2}
	c_5	23.189 kJ.K^{-1}.m^{-2}
	L_{tube}	60 m
	D_{in}	90 mm
Solar flow control	ΔT_{on} / ΔT_{off}	5 K / 2 K
	ΔT_{reg}	10 K
	$\dot{m}_{min,Sol}$	7.5 kg.h^{-1}.m^{-2}
	$\dot{m}_{nom,Sol}$	25 kg.h^{-1}.m^{-2}
Storage tanks	$V_{sto,Sol}$ / $V_{sto,Bio}$	2 m^3 / 2*12 m^3
	$H_{sto,Sol}$ / $H_{sto,Bio}$	2.5 m / 5 m
	e_{sto}	100 mm
	λ_{sto}	0.04 W.m^{-2}.K^{-1}
Biomass boiler	$Q_{nom,Bio}$	1250 kW
	$Q_{min,Bio}$	375 kW
Gas boiler	$Q_{nom,Gas}$	2500 kW

The fluid in the solar collectors is a mix of 47 % propylene-glycol and water. Flow rate in collector loop $\dot{m}_{Sol}$ is controlled using parameters of Tab. 1 and the following rules:

- If $\dot{m}_{Sol} = 0$ and $T_{out,Sol} > T_{r,DH} + \Delta T_{on}$ then $\dot{m}_{Sol} = \frac{G^{*}*S}{c_p*\Delta T_{reg}}$ and $\dot{m}_{min,Sol} < \dot{m}_{Sol} < \dot{m}_{max,Sol}$;
- If $\dot{m}_{Sol} > 0$ and $T_{out,sol} < T_{DH,r} + \Delta T_{off}$ then $\dot{m}_{sol} = 0$.

The mass flow rate crossing the heat exchanger on the DH side equals to $\dot{m}_{sol}$. Concerning the biomass loop, the boiler runs depending on two temperatures in the tanks:

- If $T_{ac2} < 85\,°C$ then the boiler is on;
- If $T_{ac5} > 89\,°C$ then the boiler is off.

The temperature and mass flow rate set point of the boiler are constant at 90 °C and 54 m^3.h^{-1}. It can operate from the 1st of October to the 31st of May. The gaz boiler is controlled as follows:

- If $T_{in,Gas} < 83\,°C$ then the boiler is on and the outlet set point is $83\,°C$;
- If $T_{in,Gas} > 83\,°C$ then the boiler is off.

The valve V3V$_{net}$ controls the supply temperature of the DH so that it equals to the set point.

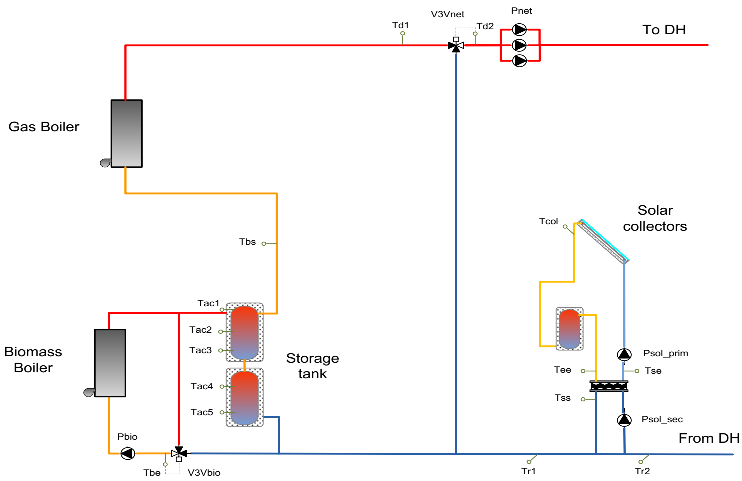

Fig. 2. Diagram of the Balma production plant

4. Solar District heating components

4.1. Pipe

Models description

The Type 604 TRNSYS component (TESS library) is selected in the present work to model the pipes of a SDH. This component relies on a first order donor-cell discretization scheme for the convective term of the energy equation. This scheme is hereafter referred has the UDS scheme. One of the known drawbacks of the UDS scheme is to introduce artificial numerical diffusion. To avoid this, a third order discretization scheme, namely the QUICK scheme (Leonard, 1979), was introduced in the model of pipe of our Modelica *DistrictHeating* library. This component needs to be carefully designed for SDH applications since it is the main contributor to the calculation of the transportation time.

Tab. 2. Parameters of the pipe model

Parameter	Value
Fluid	Water
Material	Steel
u_w	1 m.s^{-1}
L_{tube}	100 m
D_{in}	150 mm
D_{ext}	160 mm
h_{ext}	40 W.m^{-2}.K^{-1}

Comparison TRNSYS/Modelica

An analytical test consisting of a straight pipe with thermal losses to surrounding environment submitted to a convective temperature step is used to compare the two models. The numerical results obtained are also compared to an analytical solution taken from (Vedat, 1966). The parameters used for the simulation scenario are presented in Tab. 2.

Fig. 3 represents the evolution of the relative non-dimensional temperature at the outlet of the pipe as a function of time for the various solutions. This variable is calculated as follows:

$$T_{rel} = \frac{T(x=L,t) - T(x=L,0)}{T_{\max(0<t<inf)}(x=0) - T(x=0,0)} \qquad \text{(eq. 1)}$$

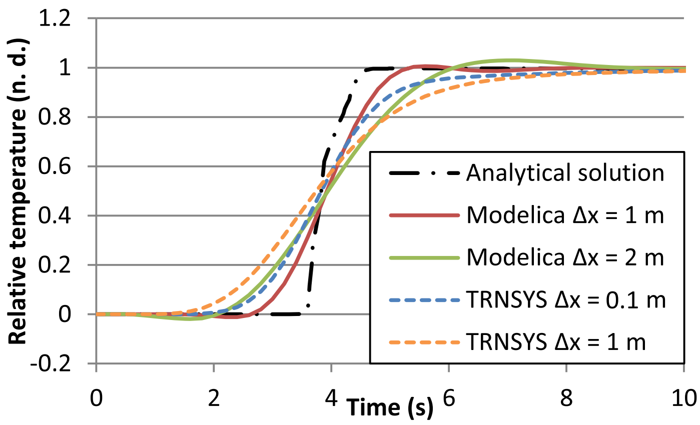

Fig. 3. Relative temperature at the outlet of the pipe

Different mesh sizes are tested for TRNSYS and Modelica models. As expected, the temperature front is more diffuse when the mesh size is large. For a same mesh size (Δx = 1m), the Modelica model shows less diffusion than the TRNSYS model. The error is then lower for the Modelica model. Tab. 3 presents the relative mean error of the models compared to the analytical solution. Even with a mesh size ten times smaller, the TRNSYS model still has a more important relative mean error.

Tab. 3. Relative mean error of the model compared to the analytical solution

Pipe model	Mean error
Modelica Δx = 1 m	10.9 %
Modelica Δx = 2 m	23.8 %
TRNSYS Δx = 0.1 m	20.6 %
TRNSYS Δx = 1 m	30.7 %

Due to the QUICK scheme, a small amplitude overshoot can be observed at the end of the temperature front in the Modelica results. This overshoot is present regardless the mesh size but its wavelength decreases with the mesh size. This is a known side effect of the QUICK scheme (Leonard, 1979).

4.2. Solar Collector

Models description

The TRNSYS solar collector model is the Type 832v500 (Perers et al., 2012). This well-known model has been validated several times with experimental values. The Modelica model has been developed in the *DistrictHeating* library. Both models represent dynamic solar collectors, using ISO 9806:2013 to calculate the heat output of the collector area:

$$\frac{Q_{out}}{S} = \eta_0 K_{\theta b}(\theta) G_b + \eta_0 K_{\theta d} - c_1 \left(T_f - T_a\right) - c_2 \left(T_f - T_a\right)^2 - c_3 u_v \left(T_f - T_a\right) - \frac{c_5 dT_f}{dt} - c_6 u_v G^* \qquad \text{(eq. 2)}$$

$K_{\theta b}$ is determined using the following equation:

$$K_{\theta b} = 1 - b_0 \left(\frac{1}{\cos(\theta)} - 1\right) \qquad \text{(eq. 3)}$$

An important difference between the two models concerns the fluid model. In TRNSYS, the fluid is only represented by its constant heat capacity. In Modelica, the fluid is thermodynamically modeled and all its properties are known (density, heat capacity, viscosity…). The heat capacity varies with the temperature according to a data table.

Comparison TRNSYS/Modelica

$T_{in,Sol}$ is chosen constant at 40 °C. $\dot{m}_{Sol}$ is regulated using the same rules than the production plant (except that $T_{r,DH}$ is replaced by $T_{in,Sol}$). The parameters used in this comparison are the same than for the solar plant (cf. Tab. 1) with $c_3 = c_6 = 0$, $K_{\theta d} = 0.9$ and $b_0 = 0.18$. The weather data are identic between the two models. They are simulated from the 1st of January to the 31st of July.

To compare these models, the produced energy is calculated for each month of the simulation, as depicted in

Fig. 4. The differences between the two models are shown in Tab. 4. The first assessment is that the models give similar results. But there are some differences. TRNSYS model produces a bit more energy than the Modelica model. There is a difference of 1650 kWh between the models for the entire simulation, which represents 0.7 % of the total produced energy.

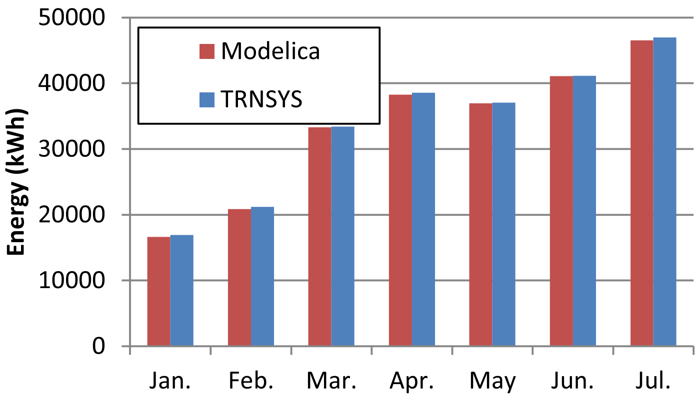

Fig. 4. Comparison of the solar produced energy between TRNSYS and Modelica per month

$\dot{m}_{sol}$ is compared in Fig. 5 to analyze these differences. Figures a) depicts the results for a sunny week in June while figure b) shows results for a week with varying weather conditions in January. The comparison illustrates that the two models present very similar results during sunny periods. Indeed, the difference of produced energy between the two models is 0.6 % during this week. When the weather is varying, the models present quite different results. The difference of produced energy is then 1.4 %. The moment when the fluid starts to flow or when it stops is not exactly the same between the two models. This can be due to the difference between the constant and variable time step solvers. Thus, when the mass flow rate often varies during a day (with a varying weather), it brings a non-negligible gap. The difference of heat capacity also brings variations between TRNSYS and Modelica models. The fluid capacity varies between 3560 and 3780 J/kg.K with Modelica while it stays constant to 3730 J/kg.K with TRNSYS. However, the two models are still quite close and their difference is acceptable.

Tab. 4 Differences of produced energy between the two models per month

	Diff. (kWh)	Rel. diff.
January	245.40	1.45%
February	318.96	1.51%
March	113.75	0.34%
April	320.77	0.83%
May	127.35	0.34%
June	60.82	0.15%
July	462.73	0.98%
Total	1649.77	0.70%

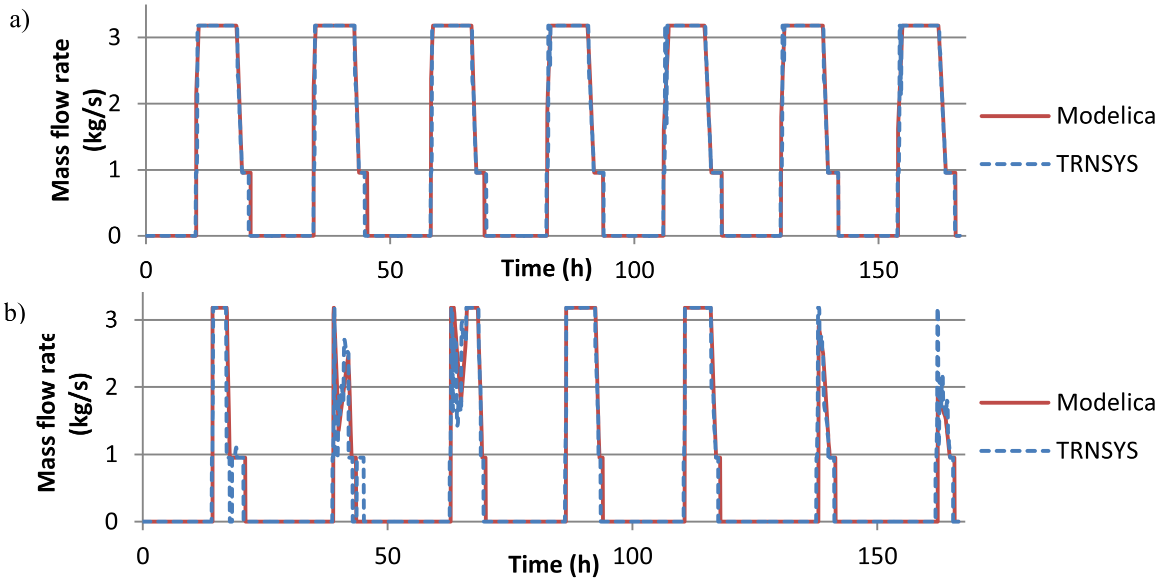

Fig. 5. Evolution of the mass flow rate during: a) a week of June and b) a week of January

4.3. Substation

Models description

The TRNSYS and MODELICA substation models have both been developed by our research group and rely on the same basis. These models are intended to be integrated in large numerically expensive DH system models. A tradeoff between precision and computational cost is therefore necessary. The substation component are modelled as a combination of a ε-NTU heat exchanger model (Shah and Sekulić, 2003) and an ideal regulator for the secondary outlet temperature. The inputs of the models are $T_{in,s}$, $T_{out,s,set}$, $T_{in,p}$ as well as the heat power demand. The outputs of the models are $T_{out,p}$, $\dot{m}_p$ and $\dot{m}_s$. $T_{out,s}$ is supposed equal to its set point, 65 °C. The heat transfer coefficient depends on $\dot{m}_p$ according to equation 4. Using the experimental results, the coefficients a and b are set respectively to 12 044 and 0.5858 with UA in W/K and $\dot{m}_p$ in kg/s.

$$UA = a * \dot{m}_p^b \qquad \text{(eq. 4)}$$

The experimental data are taken from a substation of the french Balma SDH (19th of March to the 18th of April 2014). The experimental recording time step is 15 minutes for the temperatures and 1 hour for the mass flow rate.

Comparison TRNSYS/Modelica

Fig. 6 compares $\dot{m}_p$ and $T_{out,p}$ with the experiments on a one day period (the 30th of March). Results show that the two models are very close to each other. They are also relatively close to the experimental results. Same conclusions can be drawn while analyzing the entire simulation period. Tab. 5 presents the absolute mean and maximal errors of the two models for $\dot{m}_p$ and $T_{out,p}$ compared to experimental results for the entire simulation period. Results of the two models can be supposed equal since there is only 0.0002 kg/s and 0.001 K difference between them respectively for $\dot{m}_p$ and $T_{out,p}$. The maximal errors are also very close to each other. They are equal for $\dot{m}_p$ and the difference is 0.08 K for $T_{out,p}$. It is interesting to note that all these maximal errors occurred at the same instant in the simulation.

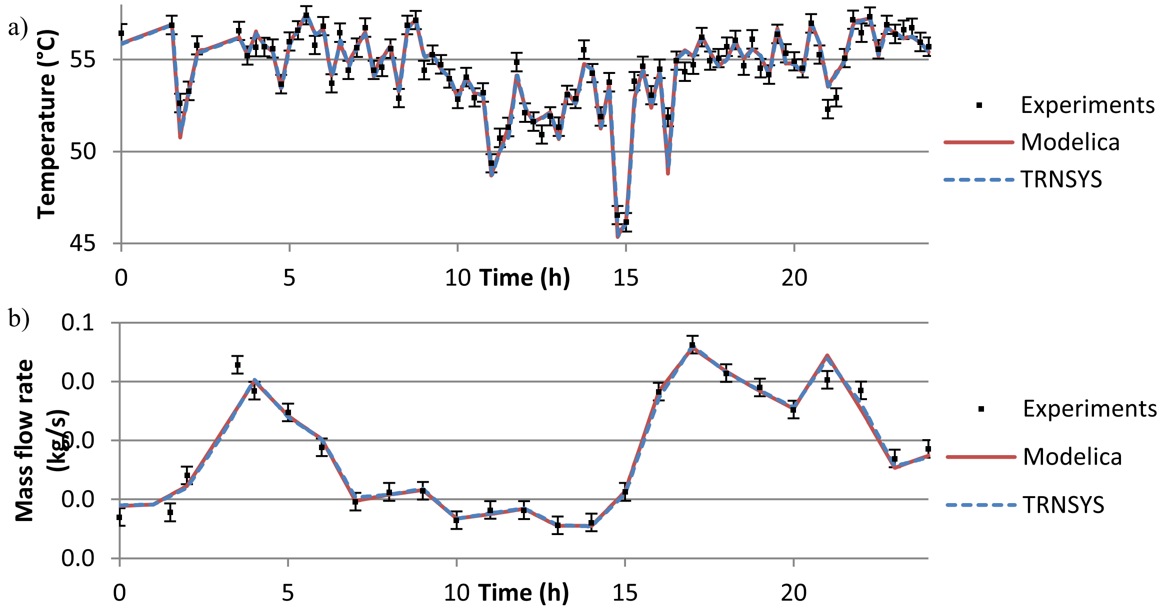

Fig. 6. Comparison of the two models with the experimental results on a 1 day period for: a) $T_{out,p}$ and b) $\dot{m}_p$

As can be seen from the above graph, the predictions of the models are also close to the experimental results. Most of the numerical results are within the experimental error band. The assumptions made to build these models (ideal regulation and power law to evaluate the global heat transfer coefficient) can be considered to be valid for SDH applications.

Tab. 5. Absolute mean error and maximal error on $T_{out,p}$ and $\dot{m}_p$ compared to experimental results for the entire period simulation

	Modelica		TRNSYS	
	$\dot{m}_p$ (kg/s)	$T_{out,p}$ (K)	$\dot{m}_p$ (kg/s)	$T_{out,p}$ (K)
Mean error	0.0144	0.334	0.0146	0.333
Max error	0.133	3.08	0.133	3.00

4.4. Components conclusions

Three component models have been compared between TRNSYS and Modelica. Solar collector and substation models present very close results. Some significant differences have been pointed out for the pipe model and are analyzed in the following. These models are integrated in SDH systems models.

5. Systems modeling

5.1. Solar District Heating Plant

Models description

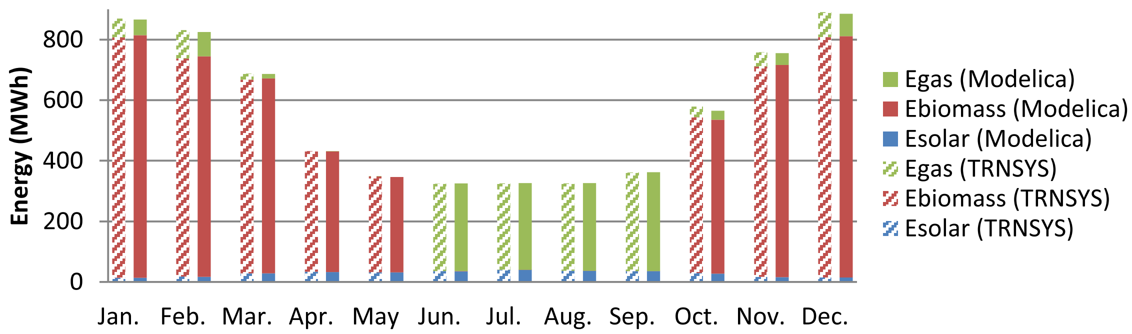

Fig. 7. Monthly distribution of the heat sources for the two SDH plant models

The SDH plant described in section 3.2 is modeled using TRNSYS and Modelica. The aim of these two models is to focus on the solar loop and on its integration on the SDH. The components models used in the solar loop are then more detailed (solar collector, solar pump, solar storage, etc.) compared to the other components. To represent the storage tanks, the Modelica model uses the *Stratified* component model from the *Buildings* library (Wetter, 2009) and the TRNSYS model uses the Type 340 (Harald Drück, 2006). An important difference between the two models relates to the control of valve. In Modelica, PID controllers are used while ideal controllers are used in TRNSYS. Firstly, monthly results are analyzed. Secondly, temperatures are analyzed on a 5 days period in January. It aims at comparing solar and global DH results between the two models.

Tab. 6. Repartition of annual heat in MWh

Source	TRNSYS	Modelica
Solar	333.4	327.1
Biomass	4871.2	4892.5
Gas	1526.4	1480.6
Heat Losses	13.8	12.1
Heat to DH	6717.2	6688.1

Comparison TRNSYS/Modelica

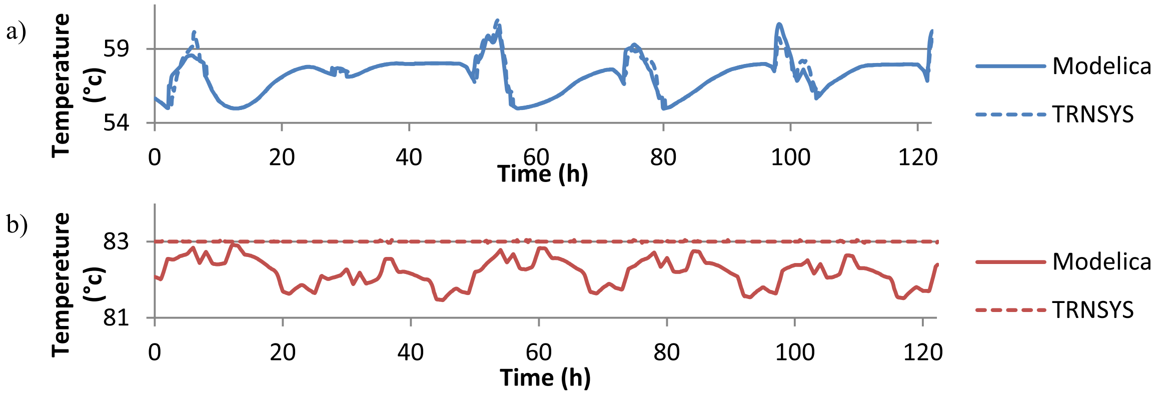

Fig. 8. Evolution of: a) $T_{out,Sol}$ and b) $T_{s,DH}$ for a 5 days period

Monthly distribution of heat sources is depicted in Fig. 7 and Tab. 6 resumes the annual heat production for each source, heat losses and heat delivered to the DH. For Modelica, annual solar, biomass and gas fractions are respectively 4.9 %, 73.0 % and 22.1 % while they are respectively 5.0 %, 72.4 % and 22.7 % for TRNSYS model. Results are very close.

Evolution of the solar and DH outlet temperatures in the SDH plant over a 5 days period in January is presented in Fig. 8. The solar loops can be considered as equivalent since $T_{out,Sol}$ of the two models are very close. In the contrary, $T_{s,DH}$ presents differences. In TRNSYS, this temperature equals 83 °C while it varies between 82 °C and 83 °C in Modelica. This is due to the PID controllers in Modelica that are used to regulate mass flow rates. The tuning of the Modelica PID might be improved and compared also with a TRNSYS PID for controlling the DH 3 way valve.

5.2. District Heating network

Models description

The two softwares are used to model the global SDH network described in section 3.2. These models aim at comparing the transportation time and the produced energy in a SDH. The pipe (mesh length Δx = 10 m) and substation models described in previous sections are used for the present simulations. For the pressure losses, Modelica model relies on a very detailed friction model taken from the Modelica standard library (Elmqvist et al., 2003). UA coefficients are chosen to depend linearly on $\dot{m}_p$. The production plant is handled via a simple boiler model neglecting internal detailed phenomena. The user demands are simulated using an external temperature dependent term, a sociologic term completed with a white noise random term. Heat losses are accounted for by considering a constant outside ground temperature of 10 °C. This is a reasonable assumption given that the pipes are buried at a depth of 1 m.

Comparison TRNSYS/Modelica

Fig. 9 depicts for both models the monthly repartition of heat demand and heat losses. The results are very close concerning the heat demand with an average difference of 0.5 % between TRNSYS and Modelica. The total energy difference over the year is 1.8 % between the two models.

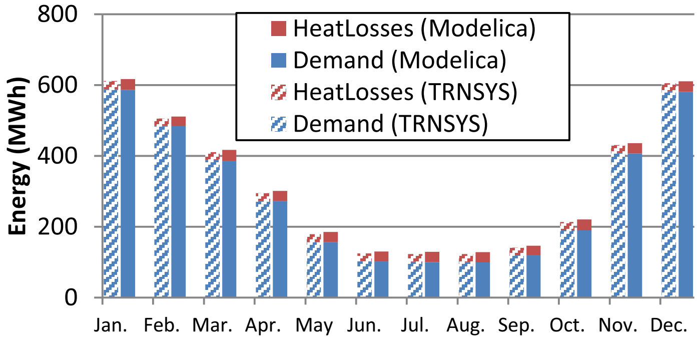

Fig. 9. Repartition of heat demand and heat losses on the network per month for the two models

Looking closer to the results, significant differences appear. The evolution of $T_{in,p}$ of the far end substation is presented in Fig. 10 on a 5 days period in January. The two temperatures have the same average of 81.9 °C. However, temporal evolutions are smoother in the TRNSYS calculation. This is most probably due to artificial diffusion introduced by the UDS scheme as already discussed in section 4.1.

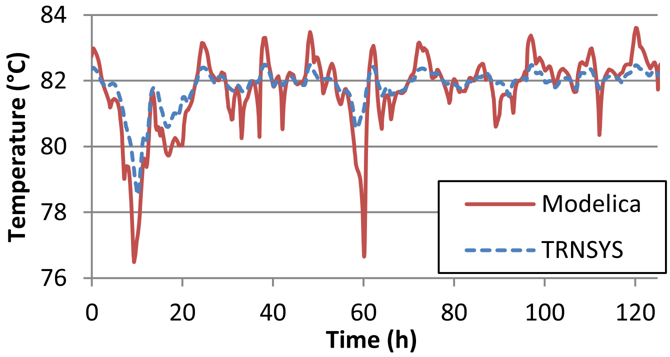

Fig. 10. Evolution of the inlet temperature of the farthest substation

6. Computational costs

Another important point especially for long term system simulation is the computational cost as they are mainly used for parametric studies in order to optimize a system. Computational costs depend primarily on the desired accuracy but also on the nature of the model and on the solvers. Preliminary results are presented in this paper in order to compare TRNSYS and the Modelica/Dymola tools. However, these results need to be completed with a sensitivity analysis performed for each software on solver tolerance, convergence criteria, integrator step …

In the comparison tests, the convergence tolerance is fixed to 10^{-6} for both tools. Concerning the TRNSYS models, the time step is fixed to 3 min for the component models and 6 min for the system models. These values are also the maximal time steps allowed for the Modelica models. As a general result it can be stated that the TRNSYS simulations are computationally lighter. However, it was not possible to end up on the determination of the computational time ratio between the two tools since modeling assumptions could not be made completely identical.

7. Conclusions

Our group at CEA-INES is currently implied in several research activity related to the optimized operation of DH and SDH. These activities require the use of thermalhydraulic modeling and simulation capabilities. An evaluation of the TRNSYS energy simulation program and the equation-based MODELICA simulation language (associated to the Dymola tool) has therefore been initiated. The present paper reports on this comparison work.

Solving hydraulics is a requirement for any simulation program intending to address a DH or SDH network with a looped architecture. This issue can be naturally addressed by the Modelica language since it encompasses native multi-physics simulation capabilities. An extension of TRNSYS simulation capabilities to include hydraulics would be a very time consuming task. Moreover, the acausal, equation-based, object-oriented nature of the Modelica language helps the programmer to significantly decrease development time. In the thermalhydraulic domain (restricted to one-phase flows) several high quality and well-documented open access Modelica component library are already available.

The present work has also established that the two approaches yield similar results when comparable modeling details are considered in both tools. Even though it was not possible to set-up a rigorous benchmarking exercise, it can be reported that computational costs are generally higher with the Modelica/Dymola solution. It is our opinion that this last drawback should not preclude the use of the Modelica-based approach. In this context, a Modelica component library is currently being developed for DH and SDH applications at CEA-INES. These library developments intend to efficiently supplement the traditional simulation capabilities based on the TRNSYS simulation program.

8. Acknowledgements

Part of this work is supported by ADEME through the program of Renewable Energy Investments for the Future (Project Smart Grid Solaire Thermique).

9. Nomenclature

a: Empirical coefficient for the equation of UA
b: Empirical exponent for the equation of UA
b_0: Angle dependence of the transmittance absorptance product
c_1: First order heat loss coefficient (W.K^{-1}.m^{-2})
c_2: Second order heat loss coefficient (W.K^{-2}.m^{-2})
c_3: Wind speed dependency of heat losses (J.m^{-3}.K^{-1})
c_5: Effective thermal capacitance of the collector including fluid (J.m^{-2}.K^{-1})
c_6: Factor for a wind dependency correction (s.m^{-1})
c_p: Heat capacity of water (J.kg^{-1}.K^{-1})
D_{in} / D_{ext}: Internal and external diameter (mm)
e_{sto}: Insulation thickness of the solar and biomass storage tanks (mm)
G_b / G_d / G^*: Beam, diffuse and total radiation incident on collector plane (W.m^{-2})
h_{ext}: Heat transfer coefficient with the ambient temperature (W.m^{-2}.K^{-1})
$H_{sto,Bio}$: Height of the biomass storage tanks (m)
$H_{sto,Sol}$: Height of the solar storage tank (m)
$K_{\theta b}$: Incidence angle modifier for beam radiation
$K_{\theta d}$: Incidence angle modifier for diffuse radiation
L_{tube}: Tube length (m)
$\dot{m}_p$: Mass flow rate of the primary side of substations (kg.s^{-1})
$\dot{m}_s$: Mass flow rate of the secondary side of substations (kg.s^{-1})
$\dot{m}_{Sol}$: Solar mass flow rate (kg.s^{-1})
$\dot{m}_{min,Sol}$: Minimal solar mass flow rate (kg.s^{-1})
$\dot{m}_{nom,Sol}$: Nominal solar mass flow rate (kg.s^{-1})
$Q_{min,Bio}$: Minimal heat power of the biomass boiler (W)
$Q_{nom,Bio}$: Nominal heat power of the biomass boiler (W)
$Q_{nom,Gas}$: Nominal heat power of the gas boiler (W)
T_a: Air temperature (K)
T_{ac2}: Temperature in the middle of the second biomass storage tank (K)
T_{ac5}: Temperature at the bottom of the first biomass storage tank (K)
$T_{r,DH}$ / $T_{s,DH}$: Supply and return temperature of the DH (K)
T_f: Fluid temperature in the solar collectors (K)
$T_{in,Bio}$ / $T_{out,Bio}$: Inlet and outlet temperature of the biomass boiler (K)
$T_{in,Gas}$: Inlet temperature of the gas boiler (K)
$T_{in,p}$ / $T_{out,p}$: Inlet and outlet temperature of the primary side of substations (K)
$T_{in,s}$ / $T_{out,s}$: Inlet and outlet temperature of the secondary side of substations (K)
$T_{in,Sol}$ / $T_{out,Sol}$: Inlet and outlet temperature of the solar collectors (K)
$T_{out,s,set}$: Set point outlet temperature of the secondary side of substations (K)
ΔT_{on} / ΔT_{off}: Temperature difference between $T_{out,Sol}$ and $T_{DH,r}$ to turn on / off the solar pump (K)
ΔT_{reg}: Set point temperature difference between and $T_{in,Sol}$ when the pump is on (K)
UA: Global heat transfer coefficient of substations (W.K^{-1})
u_v: Wind velocity (m.s^{-1})
u_w: Water velocity (m.s^{-1})
$V_{sto,Bio}$: Volume of the biomass storage tanks (m^3)
$V_{sto,Sol}$: Volume of the solar storage tank (m^3)
η_0: Zero loss efficiency of the collector
θ: Incidence angle (rad)

Q_{out}: Heat output of the collector area (W.m^{-2})
S: Surface of the collector (m²)

λ_{sto}: Wall thermal conductivity of the solar and biomass storage tanks (W.m^{-1}.K^{-1})

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