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Model development and validation for a tank in tank water thermal storage for domestic application

Roberta Padovan[a,] , Marco Manzan[a,*], Ezio Zandegiacomo De Zorzi[a], Giuseppe Gulli[b], Andrea Frazzica[b]

[a]*Dipartimento di Ingegneria e Architettura, Università degli Studi di Trieste, v. Valerio 10, 34100 Trieste, Italy*
[b]*CNR – Istituto di Tecnologie Avanzate per l'Ingegneria "Nicola Giordano", v. S. Lucia sopra Contesse 5, 98126 S. Lucia, Messina, Italy*

Abstract

The hot water tanks are the typical thermal storage systems in Solar Domestic Hot Water (SDHW) plants. In this paper a new model for ESP-r has been developed, in order to simulate a tank in tank heat storage. The tank in tank system is made up of two tanks in which the smaller, storing potable hot water, is contained in a larger buffer filled with heating-circuit water. The developed model is an enhanced version of a component already available in ESP-r. Experimental results are used to identify some parameters and to perform the validation of the developed code.

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Keywords: tank in tank; energy storage; numerical calibration; plant simulation; hot water systems

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1. Introduction

A water tank represents a convenient technical solution to boost the efficiency of a Domestic Hot Water (DHW) plant, since it is easy to install and maintain and the consumption of non-renewable energy can be reduced by the storage capacity that characterizes it. This is the reason why this solution represents the most viable choice to store energy in domestic plants especially if renewable energy resources are employed such as in the case of Solar Domestic Hot Water (SDHW) plants.

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* Corresponding author. Tel.: +39-040-558-3506; fax: +39-040-572-033.
E-mail address: manzan@units.it

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The typical water tank employed for such systems is a buffer in which the DHW is contained and is maintained at high temperature through internal heat exchangers which can be fed by solar collectors and auxiliary heaters. In order to enhance the heat storage of such systems some authors have proposed the insertion of Phase Change Materials (PCM) [1] to exploit the latent effect. A model for a PCM enhanced tank component has been developed by the authors [2]. However an optimization the system highlighted the difficulties in obtaining energy savings by this technology [3] and the low effectiveness of these systems for SDHW plants has been identified with the large temperature oscillations inside the tank. An additional problem arises from the leakage danger of PCM at drect contact with domestic hot water. To avoid the aforementioned problems a different approach has been envisioned by using the so called tank in tank system in which the DHW is stored in a tank contained in a bigger buffer filled with heating system water.

Thanks to its construction features, the external tank water temperature is better controllable than in a traditional tank and the cold tap water taken from the grid does not directly affect water temperature stored in the external tank.

The aim of this work is to develop a model of a tank in tank system for the ESP-r code. In future the system will be used for the simulation of SDHW systems and will eventually be upgraded to simulate PCM enhanced heat storage tanks. ESP-r is an open source code for the integrated simulation of buildings and plants, it has been selected to develop the model thanks to the availability of the source code which permits the full control of the developed model. The storage tank component has been developed as a modified version of the stratified storage tank with one heating coil developed by Thevenard et al [4] and stored as component #103 in ESP-r plant components database. The model shares with the original component the same features such as a stratification algorithm, which guarantees the absence of inverse temperature gradients inside the tanks.

Nomenclature

A	Area [m^2]
D	Diameter [m]
G	mass flow rate [kg/s]
q	Heat flux [W]
t	time [s]
θ	Temperature [°C]
U	Global heat transfer coefficient [W/(m^2 K)]

Subscripts

DHW	domestic hot water
j	external tank layer index
k	internal tank layer index

2. Tank in tank geometry

The tank-in-tank model with one heating coil is presented in Fig. 1. The implemented component permits the user to have an internal tank for DHW inside a large buffer.

The main feature of the model is the internal tank for DHW. Usually the internal tank consists of two stacked cylinders, with the lower one of reduced diameter to accommodate one or more heating coils as shown in Fig. 1. To predict the plant behavior the model has to accommodate in some way all these features. The tank can be connected to others plant components in order to exchange water with the external tank, the heating coil and the internal DHW. An important feature of a thermal energy storage tank is the water stratification, since the hot water tends to migrate in the upper part of the tank while the colder one stratifies at the bottom. The developed model implements this feature for both internal and external tanks.

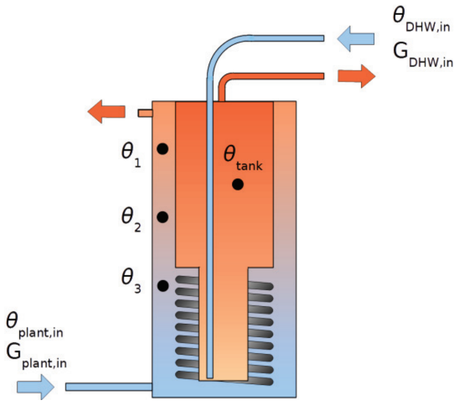


Fig. 1. ESP-r model of the tank in tank thermal storage with measurement points for data comparison.

2.1. Model discretization

The new tank component is discretized, as the rest of the plant components, through nodes which can be connected to others components to represent a plant network. In ESP-r the nodes add equations to a plant solution matrix that is solved at each plant iteration step to obtain the temperature at each node [5]. Following the method adopted by Thevenard [4] the component is solved iteratively off line, obtaining the three nodes temperatures, which represent the external tank outlet water, the heating coil exit temperature and the DHW tank outlet water temperature. The component takes into account water stratification in both internal and external tanks, therefore the tanks can be subdivided in up to 100 layers, for each layer a balance equation is written which takes into account the heat fluxes exchanged with surrounding water layers, the external environment and the heat exchangers [4]. For the present configuration however, the balance equation must take into account also the heat exchanged between the tanks, so the model deals in a consistent manner the coupling between tanks. One of the key features of the developed model is that the layer subdivision is independent for each tank; the only constraint is that the internal tank layers must be smaller than the external one, so each internal tank layer is in contact with at least two external layers.

Fig. 2 schematically illustrates the algorithm sequence. The left side of the illustration reports the routines already present in the ESP-r development version; the right side of the flow chart resumes the code implemented and the iteration performed at each plant time step.

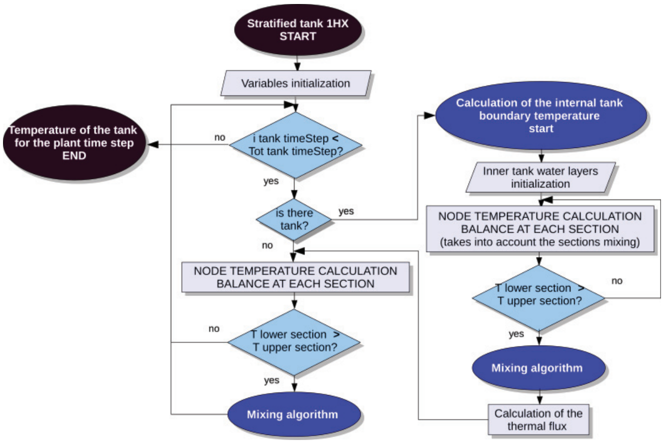


Fig. 2. Flow chart of the existing code and the new inserted code.

Particular attention has been given to the development of a matching algorithm between the internal and external tanks, since they exchange heat fluxes with a non-uniform temperature distribution due to tank thermal stratification.

Fig. 3 describes the coupling algorithm, which take into account the tank vertical discretization and the non-uniform temperature distribution. As highlighted before the vertical subdivision of the tanks is independent from each other. Figure 3 a) describes a generic situation where the indexes *k* and *j* represent generic internal and external tank layers in contact with each other.

In order to compute the temperature distribution inside the internal tank a balance equation is written for each internal layer and the external tank temperature distribution is used as a boundary condition. For each internal layer the boundary condition is computed as an area weighted average of the temperatures of the external tank layers in contact with the internal one, as presented in Fig. 3 b):

$$\theta_{avg,k} = \frac{\theta_j \cdot A_{k,j} + \theta_{j+1} \cdot A_{k,j+1}}{A_k} \tag{1}$$

In Eqn. 1 $A_{k,j}$ and $A_{k,j+1}$ are the common areas between internal tank layer k and external tank layers j and $j+1$ respectively, while A_k is the lateral area of internal layer k. After the internal tank temperature distribution has been computed, the heat transfer exchanged with the external tank is obtained as:

$$q_{k,j} = U \cdot A_{k,j} \cdot \left(\theta_k - \theta_j\right) \tag{2}$$

where U is the heat exchange coefficient between internal and external tanks. The heat flux exchanged with the corresponding internal layer can be computed as:

$$q_j = \sum_{k=1,N} q_{k,j} \tag{3}$$

The heat flux from the internal to the external tank is used to complete the heat balance equation for the internal tank layer, while N in Eqn. 3 is the number of internal layers in contact with the external one.
The implemented code takes into account also the different internal layers height due to the bottom and upper part of the internal tank, as well the different interface areas and the additional area due to the section change.

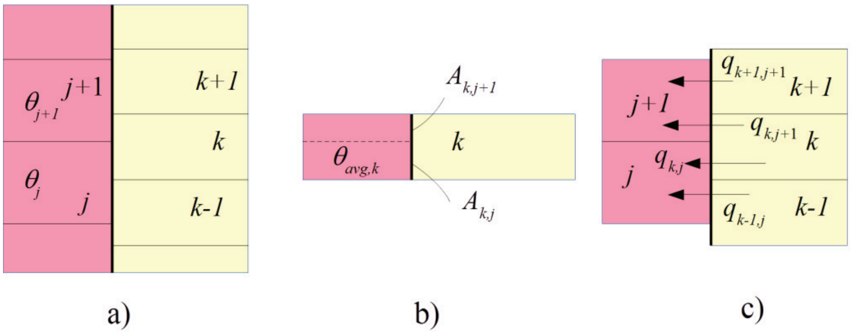
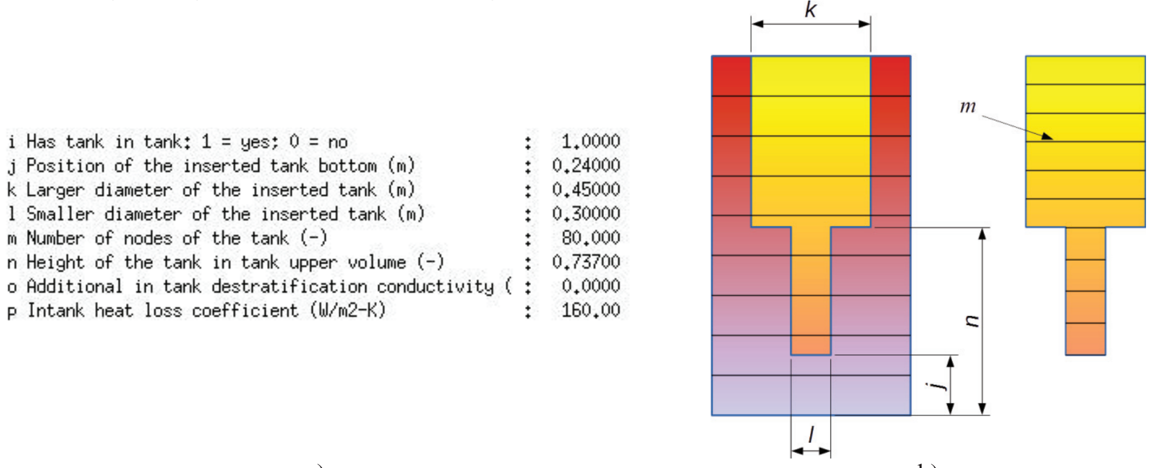


Fig. 3. Tank discretization, a) non matching layer subdivision of external (left) and internal (right) tanks, b) boundary temperature for internal layer balance equation, c) heat fluxes exchange between internal and external tank.

A particular feature of the adopted model is the mixing algorithm which is invoked when a temperature inversion occurs, that is when a tank layer has a temperature less than the one of the lower layer. When this situation occurs, the algorithm mixes the layers obtaining an average temperature. The mixing algorithm applies to both internal and external tanks in order to avoid nonphysical temperature distributions.

2.2. User component insertion and graphical interface

The new version of the tank model requires some additional input data to characterize the internal tank geometry. Fig. 4 a) reports a screen-shot of the input menu of ESP-r with the additional parameters, while Fig. 4 b) describes the meaning of the geometrical parameters of Fig 4 a).



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i Has tank in tank: 1 = yes; 0 = no                   :   1.0000
j Position of the inserted tank bottom (m)            :  0.24000
k Larger diameter of the inserted tank (m)            :  0.45000
l Smaller diameter of the inserted tank (m)           :  0.30000
m Number of nodes of the tank (-)                     :   80.000
n Height of the tank in tank upper volume (-)         :  0.73700
o Additional in tank destratification conductivity (  :   0.0000
p Intank heat loss coefficient (W/m2-K)               :   160.00
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a) b)

Fig. 4. Parameters introduced to describe the internal tank a) and geometrical meaning of the parameters b).

Other parameters which affect the model are also defined, such as the overall heat transfer coefficient, parameter *p* and the additional destratification conductivity, parameter *o*.

3. Validation

The new tank model allows the simulation and optimization of plants featuring a tank in tank system, usually employed for SDHW systems. However in order to verify the accuracy of the model a validation test has been carried out comparing numerical results with experimental data obtained by the National Research Council (CNR) at the CNR ITAE laboratories of Messina.

The tested tank has a total volume of 550 liters with an internal tank volume of 150 liters. The experimental data used to compare the numerical results are the time dependent temperatures at three positions in the external tank and one position inside the internal as reported in Fig. 1. The measures were recorded during two different types of experiments. The former is the cooling down test in which the tank is heated up and then cooled down in free air, in the latter the tank is firstly heated to a predefined temperature, then cooled down by intermittently circulating cold water inside the internal tank, simulating an intermittent request of DHW.

3.1. Experimental setup

The experimental activity was performed by means of a properly designed test rig. It was designed in accordance to the specifications reported by the standard EN 12977-3, and built at the CNR ITAE laboratories. Accordingly, it allows to carry out all the specified tests for the full characterization of a domestic hot water storage. Moreover, it can be employed for the simulation of different draw-off profiles, typical of domestic applications.

Fig. 5 reports the hydraulic scheme of the test rig. Basically it is made of two sections:

- the one at high temperature for charging phase

- the one at low temperature for discharging phase.

High temperature heat source is represented by a 24 kW electric boiler, which employs a diathermic oil as heating carrier. A plate heat exchanger (HEX 1 in Fig. 5) transfers heat from the oil loop to the water loop. A buffer vessel, 100 litres volume, is then employed to smooth the fluctuation of the temperature to be provided to the heat storage under test, 3 in Fig. 5. The tank is connected also to the discharging side by an intermediate plate heat exchanger, HEX 2. Moreover, an automatic mixing valve, 5 in Fig. 5, allows to set the water temperature to be delivered to the user during the discharging phase. Low temperature source can be simulated either directly employing tap water or by a 12 kW electrical chiller, which allows to set a quasi-constant temperature.

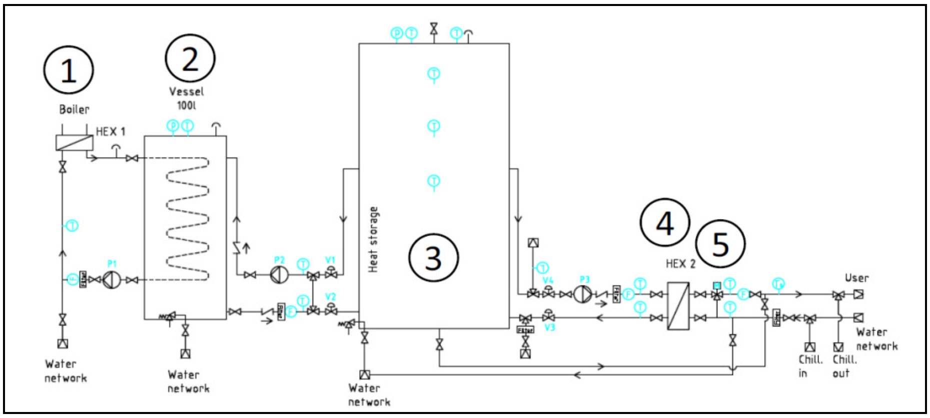

Fig. 5. Hydraulic scheme of the heat storage test rig: 1, electric boiler high temperature heat source, 2 intermediate buffer, 3, heat storage under testing, 4 intermediate HEX on the energy withdrawal side, 5 automatic mixing valve.

The test rig is fully automatized, by means of a Labview software which is able to drive all the electric valves and pumps and also to acquire all the needed data for the evaluation of the heat storage performance (temperatures and heat flows). The temperature is measured by means of thermocouples "type T" (characterized by an accuracy of ±0.5°C), while the flow rate is measured by means of an ultrasonic sensor, able to work with different kind of fluids, having a measuring range between $G_{min}=0.016$ dm^3/s and $G_{max}=1.66$ dm^3/s. The measuring error curve of the flow sensor shows an error, in the measuring range, of about 1% of the measured value. Starting from the metrological characteristics of the employed sensors, an analysis of the experimental error has been done, according to the international standards. Considering an accuracy of 0.5°C for thermocouples, and 1% of the measured value for flow rate sensor, the error on the power measurement can be computed by the following expression:

$$u(P)=\sqrt{\left[(C_P\cdot\Delta\theta)\cdot\frac{0.01\cdot G}{\sqrt{6}}\right]+\left[(G\cdot C_P)\cdot\frac{0.5}{\sqrt{3}}\right]^2} \tag{4}$$

Where u(P) [kW] represents the error, C_p, the fluid specific heat, $\Delta\theta$, the measured temperature difference across each component and G, the mass flow rate. Of course this value changes sensibly with the testing conditions. In general, especially during the discharging phases, thanks to the high employed flow rate and temperature difference measured, a really low experimental error, about 2%, was calculated.

3.2. Esp-r model

In order to test the component a simple ESP-r plant network mode has been developed as presented in Fig. 1. Only the part directly connected to the tank of Fig. 5 has been simulated, since the inlet temperatures and mass flow rated obtained from the experiments have been used for the numerical simulation avoiding the simulation of others components such as boiler and heat exchangers. Specific controls have been used to insert the experimental data, read from files, in order to synchronize the experimental results with numerical data.

3.2.1. Cooling down test

The test is divided into two phases: in the first one a hot water flow rate is injected into the external tank and it warms also the DHW contained in the smaller tank. The discharge test starts when a uniform temperature has been reached. This test has been carried in order to identify the heat transfer coefficient of the tank. This value is difficult to elaborate from the tank drawings since the tank features different insulation thickness. Fig. 6 reports the time development of the discharge data with a heat transfer coefficient U=0.926 W/(m^2 K) as can be seen the agreement is quite good, demonstrating that the model can represent well the experimental results.

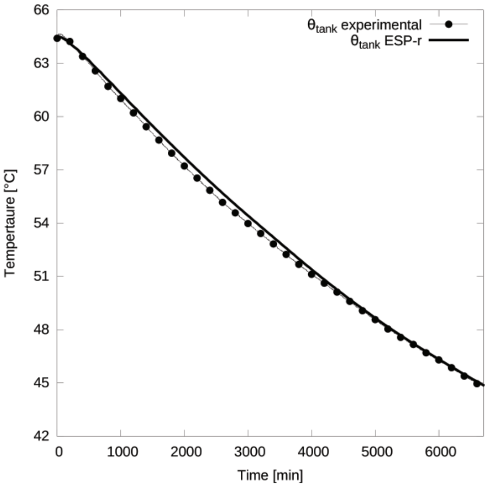

Fig. 6. Comparison of the tank temperature evolution during the cooling down test.

3.2.2. Intermittent discharge test

The test is divided into a charging phase in which a hot water flow rate rises up the tanks temperature to the uniform value of about 65°C. After the water of both tanks has reached a uniform value, the discharging phase starts. The discharge is characterized by a cold water flow inside the internal tank, $\theta_{DHW,in}$ of Fig. 1, for about 10 min alternated to a free cooling down for about 50 min. Fig. 7 reports the time behavior of the temperature at three locations inside the external tank and one location at the internal one, as presented in Fig 1. The same figure reports the time distribution of inlet temperature and mass flow rate $G_{DHW,in}$ at the bottom. The model matches the experimental results quite well and it can correctly identify the water stratification in the external tank during the discharge period. The main discrepancies are in the values of temperature θ_3 but with a temperature difference of 3 K. This result is quite good since the implemented model is one-dimensional and it cannot take into account exactly the water distribution inside the tank.

Conclusions

Solar domestic hot water systems can use a tank in tank heat storage system, but such a model is not currently available in building and plant simulation codes. To overcome this problem a new model has been developed for the ESP-r code. The paper presents the model, based on an already available plant system component, highlighting its major features and additional component parameters. The model has been also validated against experimental data obtaining good results, in particular, two comparisons were performed. The former is a cooling down test, while the latter is an intermittent discharge test. Both tests showed that the model could replicate with sufficient accuracy the experimental results. In the future the component will be extended to simulate the use of PCM in order to exploit also the latent effect.

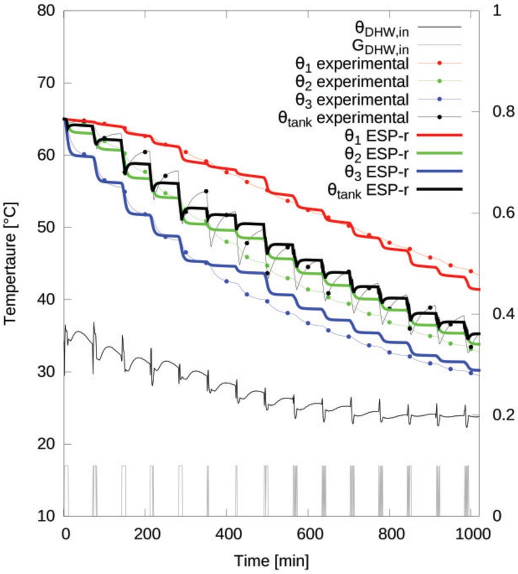

Fig. 7. Comparison between numerical and experimental data for the intermittent discharge test.

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