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State of charge estimation of thermal storages for distributed generation systems

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Abstract

The aim of this work is the development of three different models to calculate the enthalpy content of a stratified water thermal storage tank from discrete temperature measurements. The difficulty related to enthalpy value evaluation comes from the discrete temperature measurement along the storage (often only 2 to 4 temperatures along the volume height are known): the actual temperature distribution between two subsequent probes is unknown. Three different models based on three different approaches were developed and compared, basing on experimental data. A first model calculates the enthalpy value considering the measured temperatures and the thermal power difference between generation and consumption. The second model uses a mathematical pre-defined temperature shape fitted considering real-time experimental data. The latter model is based on a 1-D physical approach using a multi-nodal method. All the models were validated against the experimental data obtained from the distributed generation laboratory installed in Savona, Italy.

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Nomenclature

A	section [m^2]
c	speed [m/s]
q	heat flux [W]
T	temperature [K]
t	time [s]

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z	storage vessel height [m]
Δ	difference
ρ	density [kg/m^3]
Subscripts	
c	conduction
conv	convection
i	node number
m	mass flow
s	stratification

1. Introduction

To operate polygeneration grids [1] equipped with a thermal storage device, it is essential to evaluate its enthalpy content **Errore. L'origine riferimento non è stata trovata.**. If this component is simply based on sensible heat storage (e.g. hot water), this calculation is rather complex (usually the vessel is equipped with a small number of temperature sensors). For this reason, the Thermochemical Power Group (TPG) of the University of Genoa developed three different models to evaluate the thermal storage enthalpy considering three different approaches: empirical (model n.1), mathematical (model n.2) and physical (model n.3).

2. Test rig description

In the framework of the European Collaborative project called E-HUB, the TPG developed a new experimental facility for optimization activities on smart polygeneration grids. This rig (Fig.1) is based the following technology (both electrical and thermal energy **Errore. L'origine riferimento non è stata trovata.**[1]): a 100 kWe recuperated micro gas turbine (T100 PHS Series), a 20 kWe internal combustion engine (TANDEM T20-A) and a 5000 l storage tank (the thermal grid is based on a two ring layout as described in **Errore. L'origine riferimento non è stata trovata.**[1]).

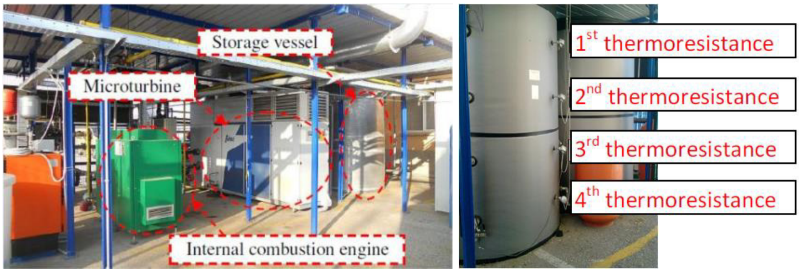

Figure 1. Test rig and storage tank.

3. Models

3.1. Empirical approach (model n.1)

Since the temperature distribution inside the vessel is stratified, it is possible to define a separation surface (or better a separation zone) between the charged part (at the generation temperature level) and the discharged one (at the return temperature value). So, from the temperature sensors it is possible to calculate the enthalpy value for the vessel zones completely at high or low temperature levels. For the intermediate zone no direct information is available from measurements. So, the thermal power difference of the connected devices is used with an integration approach considering the thermal power difference between generation and consumption. Since this approach is significantly affected by thermal losses and measurement errors, it is necessary to compensate the model introducing an empirical value stated from previous experiments. An accuracy related to this compensation is essential to avoid significant errors during long time tests. Moreover, to avoid discontinuous behaviour between the fully charged or discharged parts and the intermediate zone, a linear connection was introduced.

3.2. Mathematical approach (model n.2)

This model is based on the calculation of a continuous function able to represent temperature distribution inside the vessel (mono-dimensional approach). This equation (Eq.1) shows the vessel temperature in correspondence of a height level (z) on the basis of 5 parameters (a, b, c, d, e) calculated with a fitting tool named Constrained Nonlinear Curve Fit LM Bounded. It fits a curve using a “first try” set of parameters into a Levenberg-Marquardt algorithm. Furthermore, the result parameters are coerced into a defined bound, set to ensure the physical plausibility of the solution.

$$T(z) = \frac{e\cdot(d\cdot z - a)}{\sqrt{c+(d\cdot z-a)^2}} \ln\sqrt{c+(d\cdot z-a)^2} + b \tag{1}$$

Finally, the vessel enthalpy is calculated with a sum process. This component is modeled like a stack of one centimeter height elemental volumes; for each volume the temperature (calculated with Eq.1) is considered constant for all its internal points.

3.3. Physical approach (model n.3)

This model is based on the multi-nodal method, which divides the storage in sections (nodes) and writes the energy balance (Eq.2), considering different internal and external phenomena (heat conduction between the various masses of water, heat convection between the masses and the outside, a dissipative term, inlet or outlet water flow rate , internal natural convection).

$$\frac{(\rho \cdot c \cdot A \cdot \Delta z)}{2} \cdot \frac{dT_i}{dt} = q_{c,i} - q_{conv,i} + q_{s,i} + q_{m,i} \tag{2}$$

The system is constituted of N differential equations, that can be numerically integrated: for the mathematical integration with time the implicit Crank-Nicolson method was implemented. The model was validated in [3]. In the real application, the model estimates the remaining temperatures and it is real-time forced with the temperature measured for a more accurate calculation of the state of charge [3].

4. Model results and comparison

The test was started with the storage charging level at about 72% of its maximum. The thermal power difference between generation and utilization was close to zero during the initial 17000 s. Then, an excess of thermal consumption (power difference: about 51 kW average value) is followed by a generation value significantly higher than the utilization (power difference: about 38 kW average value). The enthalpy was calculated considering 55°C as reference temperature. For this reason, Fig.2 shows (for all the models) an almost constant trend in the initial part followed by a sensible decrease and its final increase.

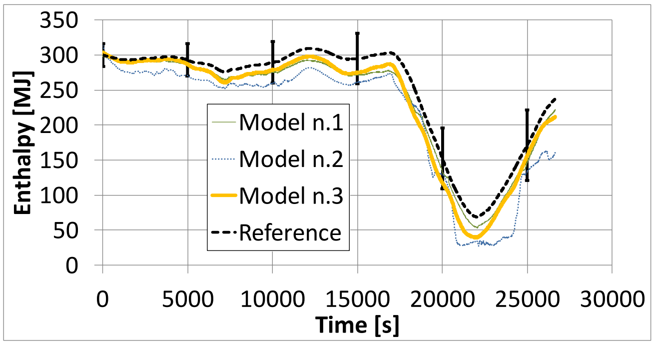

Figure 2. Model comparison and validation (thermal storage enthalpy content).

The results show that the three models are in good agreement with the reference (almost inside the uncertainty band calculated with probe uncertainty values **Errore. L'origine riferimento non è stata trovata.**[1]). However, this reference (a simple thermal power integrator based on the difference between thermal power generation and consumption) is not accurate for long time tests for measurement errors. Model n.1 shows a good behaviour in significant agreement with the most complex one (the Model n.3). However, some few discontinuities (5% order of magnitude) are present. Model n.2 is showing a more discontinuous behaviour due to temperature fitting problems and to inlet/outlet temperature fast variations. Model n.3 is the most reliable (closest trend with the reference) for its physical approach which is able to compensate thermal losses and power measurement errors.

5. Conclusion

These results show a good agreement with the reference. Since the complete physical approach is the most accurate, both empirical and mathematical methods can be used for calculation time saving. The physical model will be also used in combination with a model predictive control in future TPG's activities.

Acknowledgements

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Biography

Iacopo Rossi obtained his degree in Mechanical Engeneering with honours in 2013. At the moment he is Ph.D. student of TPG at University of Genoa working on dynamic and control of energy systems.