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Thermal storage of sensible heat using concrete modules in solar power plants

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Abstract

Guidelines for designing a concrete storage module and for its integration into a solar plant, respecting constraints linked both to an adequate solar field operation and to the production system based on ORC, are described. A series of simplified procedures are developed to be used for a first module design and more sophisticated (even if more expensive) simulation techniques via the Finite Element Method are checked and upgraded. Once the ongoing experimental phase on a scaled storage prototype at the ENEA site of Casaccia has been concluded, the obtained data will be used for completing both the setup of the calculation instruments and the R&D activity dealing with the development of an appropriate concrete mixing, optimising its chemical–physical and durability performances, and with the module integration within a CSP system.

Keywords: Thermal storage; Sensible heat; Concrete; Durability

1. Introduction

Technologies and methods for thermal energy storage have been well tested in CSP – Concentrated Solar Power – plants (Giannuzzi et al., 2007; Salomoni et al., 2008). Solar tower plants (e.g. Solar Two, USA) and advanced parabolic trough plants (e.g. Archimede by ENEA, Italy) use molten salts both as heat transfer and thermal storage fluid. Differently, traditional trough plants (e.g. Andasol, Spain) distinguish the fluid through the solar field (synthetic oil) from the one used in the storage system (molten salt). Hence, storage applications have only been proven in liquid state and in large scale plants.

Concrete is the generally preferred "solid" material for its low cost and good thermal conductivity, already tested at the Platform Solar of Almeria (Spain) and by DLR (Germany) revealing an appropriate response to the specific use, among which a structural stability (Laing et al., 2006, 2009).

Thermal storage of sensible heat using concrete is at present a known procedure, but applications are still

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limited and some variables (e.g. concrete durability, concrete mixing, etc.) are unclear or not appropriately defined. Briefly, limitations of existing solid thermal energy storage systems include: existing systems are conceived for operating in big capacity plants (skilled personnel and technical infrastructure available); concrete mixtures: actual research is focused on thermal performances optimisation regardless costs and durability issues; hygro-thermal issues, not well defined, has not been treated and disseminated.

Nowadays, new mixtures are under study but their characterisation seems to be not completed.

Some attempts have been tried incorporating components to increase the conductivity of the composite materials as graphite but this solution increases the cost, however no experience exists in concrete. The technology of concrete production can also contribute to the optimisation of the type of concrete for TES (Thermal Energy Storage), as for instance self compacted concrete.

The main technical objectives of the authors' current research include: (1) development of an appropriate concrete mixing, optimising chemical–physical and durability performances in a temperature range up to 300 °C; (2) thermal sizing of the storage module and its integration within a CSP system. Such results will be obtained through various activities, for some part reported in this paper: • verification of the (hydro)-thermo-mechanical response for the storage module, in its start-up and service stages; • realisation and experimentation of a prototype at reduced scale; • conceptual Project of a thermal storage module, including a synthesis of both technical and economical aspects.

Among the innovative research and development items, we recall:

(a) The system is constituted by modular blocks made by innovative concrete material whose mix design is being investigated (Salomoni et al., 2011; Ozger et al., 2013). The constitutive characterisation of the concrete mixture chosen as thermal storage, from both the theoretical and the experimental viewpoint, will represent a fundamental cognitive relapse in the context of cementitious materials subjected to high temperature (Di Maggio et al., 2007). In its basic aspects it will be inspired by complementary applications within an already operative Project (SolTeCa Project) to which ENEA, and the Universities of Padua, Trento and Rome, Italy, are contributing. The research outcomes have already proved the possibility to satisfy the features and behaviour requested for such an application in terms of thermal and mechanical characteristics. It is anyway necessary to deepen the structural behaviour and aspects regarding durability and possible local small damaged spots which can bring to a possible loss in functionality of the component, being nowadays an open question.
(b) The tubes in which the heat-transfer fluid flows are immersed inside the concrete matrix. The up-to-now adopted constructive solution used by DLR consists in a tube bundle with adequately supported pipe fittings and in a particular distribution within concrete casting (Laing et al., 2006, 2009, 2011; Tamme et al., 2004). A sort of concrete mono-block comes out: the free water contained within its concrete matrix, hardly leaks, especially during its first heating phase. This can bring to high pressure gradients, causing complete component damage or reductions in thermal performance.

Our research activity will match a wide application range of expertise in order to avoid relevant problems of module cracking. A balanced new-type concrete mixture, derived from previous researches, will be cast under innovative procedures. Piping would derive from heat exchanger applications with special interface layers also experienced in nuclear plants. Start-up and operational phases would be conceived to limit matrix pressure stress.

2. The SolTeCa Project

The SolTeCa Project contextualizes TES in solid media within the Italian context; the main objectives of the Project include:

– development of an appropriate concrete mixing so to optimise its chemical–physical properties, durability and performance at temperatures between 80 and 300 °C;
– thermal design of a storage module and its integration in CSP systems.

The Project is addressed to solar plants with innovative aspects and characteristics such as: small size plants with a peak power between 0.5 and 5 MWe, to be more easily placed in the territory; sensible heat storage in concrete with ad hoc mixing; modular structure of the storage system with elements of reduced dimensions so to be pre-cast and to limit the efforts during degas phases at start-up; capability of returning energy to the heat-transfer fluid at temperatures between 120 and 300 °C; limitation of the storage specific cost between 20 and 30 €/kW h_th; use of a heat-transfer fluid with low environmental impact (possibly water); coupling of the solar plant and the storage system with ORC (Organic Rankine Cycles) groups and biomass plants.

It is to be underlined that the maximum operational temperature for concrete is fixed at about 300 °C; if water is chosen as heat-transfer fluid, the maximum temperature will be appropriately reduced to limit the service pressure.

As stated, TES is based on CSP systems and the technology has been developed for power plants (SPP, Solar Power Plants) of big dimensions; most of the solar source power comes from the so-called "sun-belt", i.e. the most irradiated area of the planet such as North Africa and Middle East. Anyway the concentrated solar technology can be adopted even in Southern Europe and Italy by integrating