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Thermal energy storage for CSP hybrid gas turbine systems: Dynamic modelling and experimental validation

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HIGHLIGHTS

- Dynamic analysis of sensible type thermal energy storage by two different approaches.
- CFD model using ANSYS-FLUENT® code and a reduced-order model using TRANSEO.
- Experimental validation of the simulation results from both models.
- Comparison of modelling capability and scope of each model.
- Estimation of total thermal losses from the storage vessel.

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ABSTRACT

Integration of Thermal Energy Storage (TES) is one of the promising features of Concentrated Solar Power (CSP) technology which allows the Renewable Energy Sources (RES) to provide uninterrupted and dispatchable power supply, and thus facilitates the RES grid integration. Hybrid Solar Gas Turbine (HSGT) systems along with TES integration have gained great attention for the last decades. Numerical modelling and simulation tools are essential for the TES design optimization and analysis of its thermal behaviour during charging and discharging phases. This paper deals with the dynamic modelling and experimental validation of a TES at laboratory scale, which is part of the HSGT system. The TES is modelled with two different approaches: the CFD model using a commercial tool and a reduced-order model using the in-house transient simulation tool TRANSEO, which has been developed by Thermochemical Power Group (TPG) for the energy system dynamic analysis. The validation of both model results against the data obtained by the Authors through experimental investigation has highlighted that 2D discretization of the TES through the CFD model gives accurate representation of the thermal behaviour of the system, but it causes a significant computational expense. On the other side, 1D dynamic model reasonably predicts the time dependent thermal behaviour of TES, except some deviations from the experiments which are related to the simplified discretization scheme. However, due to its fast approach, the TRANSEO model can be effectively used to perform both TES initial design and sensitivity analysis, and also to develop or verify the control system at a later stage of HSGT system development.

1. Introduction

Global climate change, fluctuating prices and restrained supply of conventional fuels urge immediate measures to be taken in order to curtail the greenhouse gas emissions from the fossil fuel fired power plants. The accelerated deployment of Renewable Energy Sources (RES), and adopting new technologies for energy production can help the emerging economies through provision of clean and secure energy supply, without compromising their economic growth [1–3]. Concentrated Solar Power (CSP) is one of the promising and rapidly expanding renewable energy technologies, owing to its features like wide availability, readiness for hybridization and cost effectiveness. One of the CSP strengths is the integration of Thermal Energy Storage (TES), which facilitates the uninterrupted energy production after sunset and during cloudy days. This significantly increases the CSP capacity factor, thus giving it an edge over solar PV and other renewables. It also enables the dispatchable power generation, which can facilitate both the grid integration and economic competitiveness of

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Nomenclature

Variables

T	temperature [°C]
t	time [s]
V	flow velocity [m/s]
p	pressure [bar]
S_i	source term for the ith momentum equation
k	thermal conductivity [W/m K]
C_p	specific heat capacity [J/kg K]
ε	porosity
α_{fs}	interfacial area density [area of the fluid/solid interface per unit volume of the porous zone, m^{-1}]
α	permeability [m^2]
μ	dynamic viscosity [Pa s]
h	convective heat transfer coefficient [W/m^2 K]
ṁ	mass flow rate [kg/s]
$e_{rel.t}$	relative percent error at time t
m	mass [kg]
r	radius [m]
L	length of the storage [m]
Q	energy [J]
U	heat loss coefficient [W/m^2 K]

Subscripts

c	charging
d	discharging
out	outlet
f	fluid
i	any point inside TES
ins	insulation
in	inlet
min	minimum
max	maximum
s	solid

Abbreviations

CSP	Concentrated Solar Power
CRS	Central Receiver System
HSGT	Hybrid Solar Gas Turbine
HTF	Heat Transfer Fluid
LTNE	Local Thermal Non-Equilibrium
mGT	micro Gas Turbine
CHP	Combined Heat and Power
RES	Renewable Energy Sources
RTD	Resistance Temperature Detector
RANS	Reynolds-Averaged Navier–Stokes
RMS	Root Mean Square
SGTU	Solar Gas Turbine Upgrade
TES	Thermal Energy Storage
UDF	User Defined Function
PCM	Phase Change Material

CSP power plants [4].

The interest for solar hybrid systems like solar-biomass hybrid plants [5], solar-geothermal hybrid plant [6] and hybrid solar gas turbine systems particularly with micro gas turbine [7], is fast growing. Several recent projects in Europe focused on the integration of gas turbine systems with solar energy; their context has been described briefly in the following section.

The SOLGATE Project was started in 2002 by ORMAT industries in Spain, where a solar hybrid test system was developed, built and tested. This system consisted of a modified 250 kWe turbine, two pressurized volumetric receivers and one tubular receiver in series. The objective of the SOLGATE project was the development of a solar-hybrid power system with direct solar heating of a gas turbine's pressurized air. The overall project aimed to prove the technical feasibility, the potential of electricity cost reduction of such a system and to gain the operational experience required to initiate a demonstration project [8].

The OMSoP project funded by the European Commission, demonstrated the integration of the solar dish and mGT system. This project was focused to develop and demonstrate the advanced technical solutions for CSP systems coupled with mGT, to produce electricity in the range of 3–10 kW. The project work principally involved the development and experimental characterization of the dish component, and the integration of the complete system, leading to a full scale demonstrative plant to be located at the ENEA Casaccia Research Centre, Italy [9].

The SOLUGAS project, first solar hybrid system equipped with a gas turbine at megawatt scale, was commissioned under the European Commission's 7th Framework Programme, in May 2012 in Spain. This involves the demonstration of a solar hybrid power system with direct heating of a gas turbine's pressurized air up to 800 °C. A complete solar-hybrid gas turbine demonstration system, heliostat field and tower were built to prove the technical feasibility, performance and potential cost reductions of the technology [10].

The PEGASE, which is R&D project funded by the European Commission's 7th Framework Programme, is aimed at removing the algorithmic barriers related to the monitoring, simulation and optimization of very large power systems. The project has produced powerful algorithms and full-scale prototypes that run the whole European Transmission Network model for state estimation, real time control, dynamic security analysis, and steady state optimization [11].

At present, it can be inferred from the referenced bibliography that technical feasibility of large solar hybrid power plants has been investigated in detail. However, integration of TES in such systems still poses significant challenges.

Thermal storage can be based upon the following basic principles: Sensible Heat Storage (SHS), where heat is stored by increasing the storage medium temperature; Latent Heat Storage (LHS), where energy is stored during the phase transition of PCM; Thermochemical heat Storage (TCS), where energy is stored in reversible chemical reactions [12].

Sensible heat storage represents the simplest and least expensive form of thermal storage. Significant research work has been carried out on SHS systems employing variety of solid materials such as rocks, metals, concrete, ceramics, sand and bricks, and the technology for their utilisation is well developed [13,14]. However, in any TES system, storage and recovery of thermal energy must be done efficiently to achieve high capacity factors. For this, TES technologies must meet several requirements: high energy density, good heat transfer between the heat transfer fluid (HTF) and storage media, thermal shock resistance, low cost, and reversibility through multiple charging and discharging cycles.

In the past decades, different TES configurations like packed beds of spherical particles and monolithic blocks have been extensively investigated by many researchers to examine the effects of several parameters such as void fraction, flow rate variations, thermal losses, particle size, packing material, and fluid inlet temperature on thermal performance of the TES [15,16]. In general, efficient thermal cycling is linked to the high degree of thermal stratification inside TES, which is affected by the aforementioned system parameters. The thermocline zone in packed beds is prone to mixing in the tank or degrading after several charging–discharging cycles, hence resulting in higher exergy