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Levelized cost of electricity evaluation of liquid sodium receiver designs through a thermal performance, mechanical reliability, and pressure drop analysis

Tim Conroy[a,*], Maurice N. Collins[a], James Fisher[b], Ronan Grimes[a]

[a] Stokes Laboratories, Bernal Institute, School of Engineering, University of Limerick, Ireland
[b] Vast Solar, Level 10, 17-19 Bridge St, Sydney, NSW 2000, Australia

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ABSTRACT

The receiver in a concentrated solar power (CSP) tower system accounts for a considerable proportion of plant capital costs, and its role in converting radiant solar energy into thermal energy affects the cost of generated electricity. It is imperative to utilize a receiver design that has a high thermal efficiency, excellent mechanical integrity, minimal pressure drop, and low cost in order to maximize the potential of the CSP system. In the present work, thermal, mechanical, and hydraulic models are presented for a liquid tubular billboard receiver in a representative CSP plant. A liquid sodium heat transfer fluid as well as a number of receiver configurations of heat transfer area, tube diameter, and tube material have been analysed. The thermal analysis determines tube surface temperatures for an incident heat flux, thereby allowing for the calculation of thermal losses and efficiency. The mechanical analysis is carried out to establish creep deformation and fatigue damage that the receiver may undergo through a life service. The hydraulic analysis is concerned with calculating the required pumping power for each configuration. Results show that thermal efficiency increases for a decreasing heat transfer area, however reducing receiver area comes at the penalty of increasing tube surface temperatures and thermal stresses. The selection of tube diameter is critical, with small diameters yielding the greatest thermal efficiency and mechanical life, however the increased pressure drop reduces the overall plant efficiency due to a necessary increase in pumping power. The optimum receiver configuration is established by finding an appropriate trade-off between thermal performance, service life, pressure drop, and material costs, by using the levelized cost of electricity (LCOE) as the objective function. The analysis highlights necessary trade-offs required to optimise the design of a solar receiver.

1. Introduction

The development of renewable energy technologies has accelerated in recent times due to concerns with the environment, energy security and depletion rates of traditional fossil fuels. Solar energy has the greatest potential of all renewable resources, with 885 million TWh falling on the earth's surface each year (IEA, 2014). In terms of electricity generation, Photovoltaic (PV) and concentrated solar power (CSP) are the two main solar energy mechanisms in use today. PV currently leads CSP in terms of commercial deployment, largely due to technological improvements and significant cost reductions in recent years. Cost effective energy storage is a significant challenge with PV technology however (IEA, 2015), meaning that a commercial system may struggle to satisfactorily meet grid demands due to its 'must take' nature and intermittent supply. The means of power generation with CSP is not dissimilar to that of a traditional coal-fired plant. CSP uses point and line focus techniques to generate thermal energy in a heat transfer fluid (HTF), which is in turn used to generate electricity using a steam turbine. The conversion of concentrated solar energy into thermal energy means that CSP can generate dispatchable electricity for the grid, through thermal storage mechanisms. The ability to store thermal energy means CSP is more flexible to grid demands than most other renewable energy technologies, with dispatchability being a key value adding asset to the system (Kolb et al., 2011). CSP is considered as a realistic candidate to supply intermediate and base load power demands (Slocum et al., 2011), and is fast emerging as a feasible technology that can alleviate fossil fuel dependence in locations with a high solar resource, projected to contribute to approximately 11% of global electricity production by 2050 (IEA, 2014).

Power tower technology is expected to play a major role in the

* Corresponding author.
E-mail address: timothy.conroy@ul.ie (T. Conroy).

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Nomenclature

a_s	solar absorptivity
A	area (m^2)
A_n, B_n	temperature Fourier coefficients
a_n, b_n	heat flux Fourier coefficients
Bi	Biot number
C_p	specific heat capacity (J/kg K)
D	diameter (m)
E	Young's modulus (GPa)
f	friction factor
F	Fourier expression
F_{view}	view factor
$G_{0,n}$	wall temperature functions
h	heat transfer coefficient (W/m^2 K)
I_o	capital cost ($)
k	thermal conductivity (W/mK)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
n/N	number
n_d/N_d	actual/allowable fatigue cycles
Nu	Nusselt number
$O\,\&\,M$	operation & maintenance ($/kW$_e$)
ΔP	pressure drop (kPa)
P	pressure (kPa)
Pr	Prandtl number
Q	power (MW)
Q''	heat flux (MW/m^2)
r	radius (m)
r_d	discount rate
Re	Reynolds number
$\Delta t_d/t_d$	actual/allowable time (h)
T	temperature (K)
$\dot{W}$	pumping power (kW)

Greek symbols

α	thermal expansion coefficient (K^{-1})
δ	Stefan-Boltzmann constant (W/m^2 K^4)
ε	emissivity
ϵ	strain
η	efficiency
θ	circumferential position (rad)
μ	dynamic viscosity ($Pa.\ s$)
ν	Poisson's ratio
ρ	density (kg/m^3)
σ/τ	normal/shear stress (MPa)

Sub/superscript

∞	ambient conditions
array	solar array
avg	average
base	baseline
conv	convection
e	electrical
el	element
error	convergence error
f	fluid
hr	hour
i/in	inside/inlet
j	iteration step
l	losses
mat	material
net	net input
o,out	outside/outlet
opt	heliostat field
p	fatigue cycle type
plant	CSP plant
pump	HTF pump
pwr	power block
q	creep loading condition
r,θ,z	radial, circumferential, axial
rad	radiation
rcv	receiver
ref	reflection
rep	replacement
si/so	inner/outer surface
th	thermal
trans	piping & storage
tube	receiver tube
vM	von Mises
yr	year

Abbreviations

CAPEX	capital expenditure
CSP	concentrated solar power
DNI	direct normal irradiance
HTF	heat transfer fluid
LCOE	levelized cost of electricity
PV	photovoltaic

future of CSP (IRENA, 2012). Tower systems can operate at higher temperatures than other CSP technologies, resulting in greater thermal storage potential and higher efficiencies in the thermodynamic power cycle (Ho and Iverson, 2014). The heliostat field and receiver contribute to a significant proportion of a plant's capital costs (Pitz-Paal, 2005); therefore maximizing the efficiency of the receiver will extract maximum potential of the heliostat field, helping to increase overall productivity and lower the cost of electricity generated. Reducing both electricity costs and capital costs is a key aim for CSP research and development, as this affects the ability of CSP to compete with other electricity generating technologies on a commercial level (IRENA, 2012).

There are a number of ways to optimise the receiver design in order to maximise thermal performance and reliability. The selection of an appropriate receiver HTF is one of the most important considerations made at the design stage, as it influences plant costs, receiver performance, and thermal storage characteristics (Pacio and Wetzel, 2013). A variety of working fluids such as water/steam, molten salts, and liquid metals have been tested and operated in liquid tubular receivers since the 1980s (Falcone, 1986). Sodium is a promising working fluid that may facilitate cost reductions and performance improvements for future CSP projects (Coventry et al., 2015). It is advantageous in receiver applications due to its large thermal conductivity and broad operational temperature range in the liquid phase (371–1156 K). The thermal conductivity of liquid sodium is nearly two orders of magnitude greater than that of molten salt, this yields heat transfer coefficients that are an order of magnitude greater (Pacio et al., 2014). Improved heat transfer performance using liquid sodium should result in reduced receiver temperatures, meaning greater thermal efficiency and reduced thermomechanical strains. In an investigation by Boerema et al. (2012), it was found that a receiver using a liquid sodium HTF can be 57% smaller in heat transfer area than an equivalent molten salt receiver, allowing for greater thermal efficiency and reduced material costs. Disadvantages associated with liquid sodium includes its low specific heat