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Preliminary design and analysis of a novel solar receiver for a micro gas-turbine based solar dish system

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Abstract

The solar receiver is one of the key components of hybrid solar micro gas-turbine systems, which would seem to present a number of advantages when compared with Stirling engine based systems and photovoltaic panels. In this study a solar receiver meeting the specific requirements for integration into a small-scale (10 kW_{el}) dish-mounted hybrid solar micro gas-turbine system has been designed with a special focus on the trade-offs between efficiency, pressure drop, material utilization and economic design. A situation analysis, performed using a multi-objective optimizer, has shown that a pressurized configuration, where the solar receiver is placed before the turbine, is superior to an atmospheric configuration with the solar receiver placed after the turbine. Based on these initial design results, coupled CFD/FEM simulations have been performed, allowing detailed analysis of the designs under the expected operating conditions. The results show that the use of volumetric solar receivers to provide heat input to micro gas-turbine based solar dish systems appears to be a promising solution; with material temperatures and material stresses well below permissible limits.

Keywords: Solar receiver; Micro gas-turbine; Mutli-objective optimization; Coupled CFD/FEM analysis

1. Introduction

The worldwide growth in demand for electrical energy has shown no signs of slowing, as a result of the increasing global population and rising levels of consumption in the developing world (International Energy Agency, 2013). A significant proportion of these new consumers are located in rural areas, which often lack access to a conventional electricity network. Due to the high costs of building new transmission and distribution lines, off-grid generation of electricity is an increasingly important option for rural electrification. Currently, the vast majority of off-grid generation involves the use of diesel generators, which are well suited to meet local demand, which is typically in the region of 5–100 kW_{el} (The World Bank, 2008). However, diesel generators have high operating costs and there can be difficulties in ensuring the supply of fuel in areas with poor infrastructure (International Energy Agency Renewable Energy Technology Deployment, 2012).

In regions with high solar energy resources, solar power offers an attractive means to reduce dependence on imported fuel while meeting energy demands in a sustainable and environmentally friendly manner. Two main technologies are currently available for off-grid production of solar power, namely photovoltaic panels and dish–Stirling units. However, despite some promising features, both technologies have their associated drawbacks: a key issue

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Nomenclature

Abbreviations

MGT micro gas-turbine
TIT turbine inlet temperature

Symbols

A surface area (m^2)
C_F inertia coefficient (−)
c_p specific heat capacity (J/kgK)
d diameter (m)
E irradiance (W/m^2)
E Young's modulus (GPa)
E_1, E_2 Ergun constant (−)
F view factor (−)
f_{sol} solar share (−)
h specific enthalpy (J/kg)
i intercept factor (−)
K specific permeability (m^2)
K_{ext} extinction coefficient (1/m)
k thermal conductivity (W/mK)
L length (m)
$\dot{M}$ mass flow (kg/s)
$\dot{m}$ mass flux (kg/m^{2}s)
n refractive index (−)
P power (W)
Pr Prandtl number (−)
p pressure (Pa)
$\dot{Q}$ heat transfer rate (W)
$\dot{q}$ heat flux (W/m^2)
$\dot{q}_v$ volumetric heat source (W/m^3)
R specific gas constant (J/kgK)
Re Reynolds number (−)
r radius, radial direction (m)
S Sutherland constant (K)
$\vec{S}$ momentum equation source term (N/m^3)
s path length (m)
T temperature (K)
t time (s)
U heat transfer coefficient (W/m^{2}K)
U_v volumetric heat transfer coefficient (W/m^{3}K)
u velocity (m/s)
$\dot{W}_{el}$ electrical power (W)
x axial distance, axial direction (m)

Greek symbols

α absorptivity (–)
α linear thermal expansion coefficient (1/K)
α_{sf} specific surface area per unit volume (1/m)
δ_{ij} Kronecker's delta (−)
ε emissivity, strain (−)
ε_p porosity (−)
η efficiency (−)
θ temperature difference (K)
μ dynamic viscosity (Pa s)
ν Poisson's ratio (−)
ρ reflectivity (−)
ρ density (kg/m^3)
σ stress (MPa)
σ Stefan–Boltzmann constant (W/m^{2}K^4)
τ transmissivity (−)
φ radiation absorption constant (−)
ϕ cell diameter (m)

Subscripts

a absorber
amb ambient
b beam
c cavity
com comparison
con conversion
cond conduction
cr crushing
d diameter
e effective
el electric
f fluid
g glass
in inlet
out outlet
par particle
r radial
rad radiation
rec receiver
ref reference
rel relative
s solid
tot total
vd void
x axial
0 initial
I, II, III principal direction indices

Superscripts

i,j finite differences nodes
sol short-wave solar radiation

with both systems is the variability in output resulting from fluctuations in the solar supply. While photovoltaic panels can be integrated with battery units in order to store unused output, and thereby increase the availability of the system, this significantly increases the cost of the electricity produced. Dish–Stirling units can integrate relatively