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Fluid flow distribution optimization for minimizing the peak temperature of a tubular solar receiver

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ABSTRACT

High temperature solar receiver is a core component of solar thermal power plants. However, non-uniform solar irradiation on the receiver walls and flow maldistribution of heat transfer fluid inside the tubes may cause the excessive peak temperature, consequently leading to the reduced lifetime. This paper presents an original CFD (computational fluid dynamics)-based evolutionary algorithm to determine the optimal fluid distribution in a tubular solar receiver for the minimization of its peak temperature. A pressurized-air solar receiver comprising of 45 parallel tubes subjected to a Gaussian-shape net heat flux absorbed by the receiver is used for study. Two optimality criteria are used for the algorithm: identical outlet fluid temperatures and identical temperatures on the centerline of the heated surface. The influences of different filling materials and thermal contact resistances on the optimal fluid distribution and on the peak temperature reduction are also evaluated and discussed.

Results show that the fluid distribution optimization using the algorithm could minimize the peak temperature of the receiver under the optimality criterion of identical temperatures on the centerline. Different shapes of optimal fluid distribution are determined for various filling materials. Cheap material with low thermal conductivity can also meet the peak temperature threshold through optimizing the fluid distribution.

1. Introduction

CSP (concentrated solar power) plants are expected to play an important role in the energetic scenarios for more efficient use of renewable energy and for the reduced emission of greenhouse gases [1,2]. It is estimated that the CSP would contribute up to 11% of the global electricity production in year 2050 [3,4].

In a CSP tower plant, the high temperature solar receiver installed at the top of the tower absorbs and transforms the concentrated solar irradiation delivered from heliostats into heat and then transfers it to a heat transfer fluid. The amount of heat carried by the heat transfer fluid will be used in a downstream thermodynamic cycle to allow electricity generation. The solar receiver, being a key component of CSP systems accounting for about 15% of the total investment [5], has a decisive influence on the overall efficiency of the plant.

Depending on the geometrical configuration, the solar receivers can be classified into different types, such as volumetric receiver, cavity receiver or particle receiver [6]. In particular, tubular receivers are widely used in present commercial CSP projects because they belong to a proven technology on concepts from heat exchanger which is relatively inexpensive and durable [7,8]. Some numerical or experimental studies on tubular solar receivers in the recent literature are summarized in Table 1. Pressurized air or molten salt are used as heat transfer fluid whereas the receiver is usually made of stainless steel or Inconel.

The lifetime of tubular solar receivers depends strongly on the thermal-mechanical stress on the material which is in close relation with the peak temperature of the receiver wall [18]. Based on the study of [19] on a pressurized-air solar receiver tube made of Alloy 617, the lifetime is estimated about 30 years while operating 10 h per day under peak temperature of 1100 K. This temperature is also considered as the threshold temperature under which the corresponding mechanical stress reaches the allowable design value that the material can afford for normal operation. When peak wall temperature reaches 1250 K, the real mechanical stress is 7.2

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Table 1
Some recent studies on tubular solar receiver (N: numerical study; E: experimental study).

Study	Study type	Geometry & material	Heat transfer fluid	Inlet working and test conditions	Outlet temperature/thermal efficiency	Remarks
Heller et al. (2006) [9]	E	SOLGATE low temperature receiver module: number of tubes = 16, multi-tube coil attached to a hexagonal secondary concentrator	Pressurized air	T^{in} = 300 °C; average irradiance = 770 kW m^{-2} 45 heliostats; air mass flow = 1.4–1.6 kg s^{-1}	960 °C/~70% (overall SOLGATE)	This low temperature receiver module design results in an average temperature increase of about 200 K for air and an associated pressure drop of 100 mbar. The maximum tube surface temperature is 950 °C at a module air outlet temperature of 550 °C.
Amsbeck et al. (2008; 2010) [10,11]	N, E	SOLHYCO-receiver: length = 2.5 m, number of tubes = 40, nickel based super alloy Inconel 600	Air	T^{in} = 600 °C; input power = 230–290 kW; open aperture and with quartz window; 38–46 heliostats; mass flow = 0.8 kg s^{-1} (N), 0.51 kg s^{-1} (E)	800 °C/~70% (N), ~40% (E)	The design outlet fluid temperature is reached in both open aperture and quartz window configuration. The low efficiency in the experiments are due to heat loss through the cavity walls and lower-than-expected mass flow.
Boerema et al. (2013) [12]	N	Single-diameter receiver: outer diameter = 25.4 mm, length = 1.5 m, wall thickness = 1 mm; Ideal flow receiver; Multi-diameter receiver; Multi-pass receiver	Molten Sodium	T^{in} = 200 °C; Centered heat flux distribution, off-centered flux distribution and alternative flux distribution, average irradiance = 737 kW m^{-2}	570 °C/~90%	The ideal flow receiver has the lowest surface peak temperature. The multi-pass receiver out-performs the other designs by reducing the risk from irradiance changes.
Rodriguez-Sanchez et al. (2014) [13]	N	Receiver height = 10.5 m; Receiver diameter = 8.4 m; total number of panels = 18; number of tubes per panel = 22; external diameter of outer tube = 60.3 mm; external diameter of inner tube = 52 mm	Molten salt	T^{in} = 290 °C; Average heat flux = 800 kW m^{-2}, maximum heat flux = 1200 kW m^{-2}; Total mass flow = 290 kg s^{-1}	565 °C/~75%	The surface peak temperature can be reduced by 100 °C and the thermal efficiency increases by 2% due to the bayonet receiver. The corrosion rate and salt decomposition ratio have decreased.
Lim et al. (2014) [14]	N, E	Cylindrical shell: length = 259 mm, diameter = 114 mm; Inlet pipes: diameter = 15.8 mm and 9.6 mm, number of pipes = 4–7; Outlet pipes: diameter = 25.4 mm; Stainless steel AISI304	Air	T^{in} = 300 °C; Heat flux = 1000 kW m^{-2}; mass flow rate = 0.0128 kg s^{-1}	736 °C/~90%	Tubular solar receiver filled with a porous medium can enhance heat transfer efficiency and reduce the surface peak temperature by 75 K.
Zhang et al. (2013) [15]	N, E	Tube: outside diameter = 14 mm, wall thickness = 1.4 mm, number of tubes = 28, stainless steel	Molten salt	T^{in} = 180–322 °C; Volume flow rate = 7.6 l min^{-1}; Input power = 37.68–118.91 kW	193–415 °C/–	The theoretical analysis predicted the outlet temperature with maximum difference of 66.32 °C and relative error of 14.69%; Prediction was not accurate when the input power varied rapidly.
Quero et al. (2014) [16]	E	SOLUGAS solar receiver: height = 65 m, inclination angle = 35° Tubes: number = 170, fine nickel based alloy	Pressurized air	T^{in} = 300 °C; Heat flux = 400–1000 kW m^{-2}; mass flow rate = 3.5–5.75 kg s^{-1}; 69 heliostats, reflective area of each = 121 m^2	800 °C/–	The pressurized air can be heated up to 800 °C and further heated with natural gas to reach the working temperature of 1150 °C.
Li et al. (2013) [17]	E	Solar receiver: surface area = 30 mm × 30 mm, fabricated from Inconel 625 powder; Channel: 12 parallel micro-channels, width = 1 mm, height = 3 mm, rectangular ribs on the top of channels; Rib: height = 2 mm, thickness = 1 mm, width = 1 mm	Pressurized air	T^{in} = 300 °C; Heat flux = 170–470 kW m^{-2}; mass flow rate = 0.431–0.862 g s^{-1}; pressure: 2–6 bar	400–660 °C/–	Micro-channel design can meet the expected demand on temperature elevation of air in CSP receivers.