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A low temperature water-cooled radiation calorimeter for estimation of concentrated solar irradiance

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ABSTRACT

Radiation calorimeter is a device for assessment of the incident local concentrated solar irradiance (CSI) onto a receiver surface. This is required to evaluate the performance of a concentrated solar thermal system using, for instance a volumetric receiver, for applications. In this paper a low-temperature water cooled radiation calorimeter (RADCAL) is presented. This is designed as a cavity based on the concept of blackbody to maximize the absorption of the incident CSI on its absorber surfaces. Solar selective coatings are deposited on its reflector and absorber surface to achieve the same and are characterized using standard methodologies. This depicts an absorptivity of 0.95 and a reflectivity of 0.87 in the desired range of the solar spectrum and is theoretically verified. The absorption of energy results in temperature rise of RADCAL, which is controlled by an external water jacket to limit its value at 100 °C for mitigating the use of pressurized water. At any instant and eventually at the steady-state the CSI is estimated following the conservation of energy principle. The developed RADCAL is experimentally evaluated up to a CSI of 800 Suns (1 Sun = 1 kW/m^2) using Joule heating. The entire heat transfer process is analysed with the developed unsteady state one-dimensional mathematical model. A comparative assessment of the measured and calculated RADCAL body temperature provides the underlying uncertainty and confirms its design basis. Furthermore, the design and given consideration allows its use in arid desert condition with dust and wind. Thus, RADCAL is likely to serve in future for evaluating concentrated solar thermal system in arid deserts.

1. Introduction

Estimation of concentrated solar irradiance (CSI) onto a receiver is required for both line and point focusing based concentrated solar thermal (CST) technologies Mouzouris et al., 2011; Ballestrín and Monterreal, 2004; Fu et al., 2016. The harnessed energy can be utilized for power generation, heating and cooling applications, which make these technologies versatile. For evaluation of such systems a reliable estimation of CSI is necessary (Ballestrín and Monterreal, 2004; Kaluza and Neumann, 2001). Various methods are used for this purpose, which are based on one or more sensors (Kaluza and Neumann, 2001; Skouri et al., 2013). The most common gages used for this purpose are the circular foil or Gardon-type (Gardon, 1953), also known as a thermogage or hycal and Schmidt-Bolter type flux sensors. The basic principle of the Gardon radiometer and Schmidt-Bolter sensor is similar. The former is based on the radial and the latter is based on the axial temperature difference by heat conduction through the sensing element and are calibrated using the black-body source; see Fig. 1a and b (Kaluza and Neumann, 2001; Ballestrín et al., 2006). Currently there are few commercial sensors, from Vatell, Captec and Hukesflux (Chen et al., 2013). The range of hukseflux sensor is between 50 and 200 Suns and the time constant is about 450 ms (http://www.hukseflux.com/product/sbg01-heat-flux-meter?referrer=/product_group/heat-flux-sensors). Vatell sensors are having a better time constant of 17µs. Its surface temperature is in between 350 and 600 °C (vatell.com/node/5). Gardon type radiometer has certain advantages in terms of the size and the response time (< 1 s) however, an over estimation of the CSI is reported (Ballestrin et al., 2003). Also, the need and the involved challenges of a standard calibration technique are reiterated by various authors (Murthy et al., 1998; Guillot et al., 2014). These are summarized in Fig. 1 including some of their advantages and disadvantages. Generally, all these sensors are calibrated at the steady-state with a liquid coolant, like water see Fig. 1c (Lawson and Mcgurien, 1953; Estrada et al., 2007). A similar method is used in a cavity-type calorimeter (CAVICAL) wherein the incident energy is absorbed on its inner wall. This sensor is reported to estimate up to 4000 Suns (1 Sun = 1 kW/m^2); see Fig. 1d (Pérez-Rábago et al., 2006). Water-cooled advanced solar technology for estimation of radiation for improved

Abbreviations: CSI, Concentrated Solar Irradiance; MFR, Mass Flow Rate; RADCAL, Radiation Calorimeter

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Nomenclature

A_o	aperture area of RADCAL
A_{surf}	heat transfer surface-area of RADCAL to fluid
A_{cf}	cross section area of water-flow
A_{cs}	cross section area of solid
B (λ, T)	black body radiation spectrum
c_{ps}	specific heat capacity of RADCAL solid
c_{pf}	specific heat capacity of water
Dh	hydraulic diameter
F	Faradays constant
Gr	Grashof number
Gz_{lDh}	Graetz number
h	average convective heat transfer coefficient
I_e	electric current
J	current density
k_s	thermal conductivity of solid material
kf	thermal conductivity of water
l	length of channel along the flow
m_f	mass-flow-rate of fluid (water)
m_s	mass of RADCAL solid
m''	mass flux or deposition rate
M	molarity
$\overline{Nu}$	Nusselt number
n	no. of electrons
pv	vacuum pressure
Pr	Prandtl number
P_1	perimeter of the insulation
P_e	electric power
P	perimeter of water channel
q''_g	heat flux (loss) through insulation
q''	heat-flux
R	average radius of curved heat transfer area
R_e	electric resistance
Re_{Dh}	Reynolds number
Rq	root mean square roughness
T_i	initial temperature (=inlet condition)
T_f	temperature of fluid (water)
T_O	temperature of water at outlet
T_s	temperature of solid
T_{mf}	bulk temperature of fluid (water)
t	time in second
T_{ms}	average temperature of RADCAL solid
λ	wavelength
W	electrodeposited mass
ρ_s	density of solid
ρ_f	density of fluid (water)
ε_f	electrode efficiency
θ	azimuthal coordinate
α	solar absorptance
ε	emittance

experiment (ASTERIX) was developed to address some of the reported limitations see Fig. 1e (Ferrier and Rivoire, 2000). In most of these devices the temperature of calorimeter is higher than 100 °C and therefore, pressurized-water is required for cooling. This needs special arrangement on-the-field and the safety standards must be strictly followed. In general, cavity-type design may be employed for mitigating heat loss, as in a receiver (Prakash et al., 2009; Reddy and Kumar, 2009; Huang and Sun, 2016; Dave et al., 2013). A tilt angle from 0 to 45° may be preferred at a low wind speed (Wu et al., 2010). Such observations may be adopted for designing even a cavity-type radiation calorimeter. Generally, the absorbers in a water-cooled radiation calorimeter are exposed to atmosphere and their deterioration is expected with dust laden wind. Therefore, these sensors are preferred for indoor use with a higher accuracy in comparison to outdoor condition. Consequently, the use of such devices in arid desert regions with a high wind-speed needs special consideration.

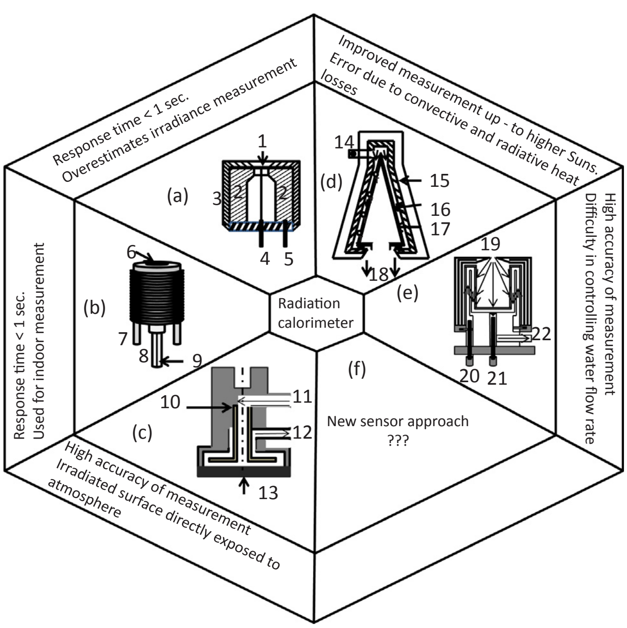

Fig. 1. Schematic of different types of measuring devices. (a) Gardon radiometer (1 constantan foil, 2 copper block (cooled), 3 shield, 4 +ve terminal, 5 −ve terminal); (b) Schmidt Boelter calorimeter (6 black coating, 7 Water cooling tube, 8 PTFE cable, 9 T type thermocouple); (c) Cold water calorimeter (10 diffuser, 11 inlet flow, l2 outlet flow, 13 circular stainless steel plate); (d) CAVICAL calorimeter (14 water inlet, 15 insulation, 16 stainless steel wall, 17 copper wall, 18 water outlet); (e) ASTRIX (19 incident beam, 20 water inlet, 21 water outlet, 22 littering).

The deposition of dust on the exposed surface may lead to an underestimation of CSI. There are few CSI measuring devices, which are working at a high temperature range (~850 °C) Ballestrin, 2002. Under such an extreme outdoor condition, absorber coating is limited and its durability is questionable (Selvakumar and Barshilia, 2012). Considering the detailed insight, challenges and limitations of such devices, an externally water-cooled low-temperature radiation calorimeter (RADCAL) is proposed, even for an outdoor application. Following literature review, this device is based on the concept of black body. Moreover, the calibration technique depending on water-cooling and the conservation of energy is adopted for its evaluation. In this design, the RADCAL temperature is limited up to 100 °C for a CSI of 800 Suns or 800 kW/m^2 that relaxes the need of pressurized-water and mitigates heat loss to ambient. Joule heating is employed for evaluation of RADCAL. A coating is deposited on the reflecting surface of RADCAL to redirect the incident radiation onto the absorbing surface (Moreno et al., 2005; Lide, 2007). The absorber of RADCAL is coated with a solar selective material to maximize the useful heat gain from the reflected solar energy (Granqvist, 1991; Behar et al., 2013; Barshilia et al., 2006). These spectrally selective absorbers should exhibit a high absorptance of ≥0.95 in the spectral range 0.3–2.5 μm and a low thermal emittance of ≤0.05 in the infrared spectral range 2.5–25 μm (Kennedy, 2002). The ceramic metal (cermet) absorber structures are commonly used due to their high spectral selectivity and the ease of integrating metal in ceramic matrix. Various physical and chemical deposition processes are explored for synthesizing cermet structures. Zynolite is commonly used as an absorber layer on the exposed surface of sensors as it creates a