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Thermal performance enhancement of solar collectors by surface geometric modifications on the heated surface, use of solar selective coatings and nano-fluids

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Abstract: Rapid depletion of fossil fuels which is our conventional source of energy and the degradation of environment have led to exploration of renewable energy sources. Solar energy is one of the most mature renewable sources of energy which provides thermal energy without any cost. Since last decade technologies used to harness solar energy have evolved as they are freely available and have commercial potential. This paper presents the advancement made in the field of solar thermal technology with emphasis on techniques employed for its thermal performance enhancement which includes geometric modifications on the heated surface of the solar collector to modify the boundary layer, use of nano-fluids to increase the thermal conductivity of the heat transfer fluid and use of solar selective coatings on the absorber surface to maximise the capturing of solar radiation.

Keywords: Heat transfer enhancement, nano-fluids, solar selective coating, solar collector, thermal performance.

I. INTRODUCTION

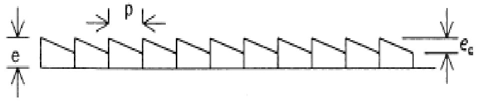
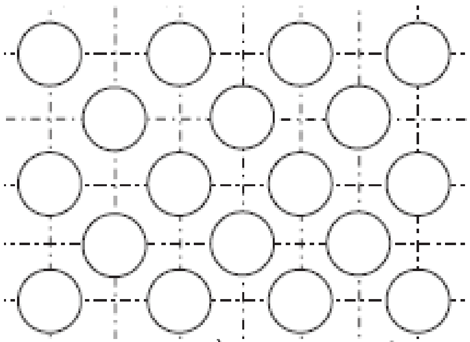
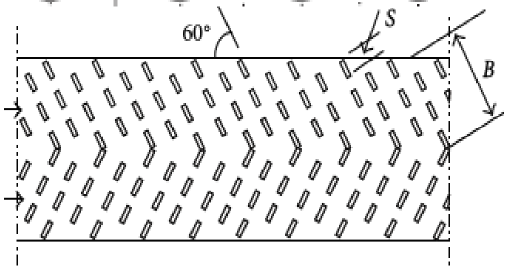
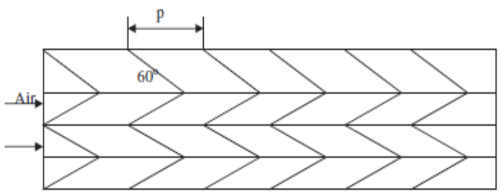
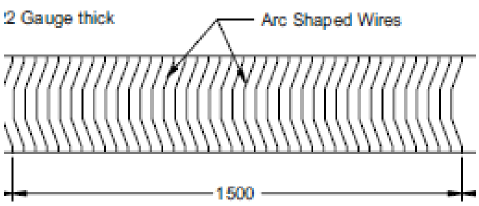
The demand of energy is increasing day by day and to meet this demand without degrading the environment has become a challenge. Use of conventional energy has led to environment degradation which is evident from the pollution, acid rain, global warming etc. that we experience. Therefore there is a need for extracting clean and green energy from renewable sources. Among all the renewable energy resources, solar energy has great potential as it is freely available, abundant, and has commercial potential too. There are two ways of utilizing the solar energy: (a) direct conversion of solar energy to electrical energy by using photovoltaic solar cell (b) conversion of solar energy into thermal energy using solar collectors. The effectiveness of solar thermal system depends on how efficiently the collector is able to capture the solar radiation and transfer it to the heat transfer fluid flowing through it. Thermal performance enhancement is an important matter of concern for energy conversion as it has economic implications too. The methods and relevant studies are discussed in subsequent sections.

II. GEOMETRIC MODIFICATIONS

Principally the heat transfer between a fluid and a surface can be increased by increasing the contact area that is using extended surface and secondly by creating a turbulence which enhances the mixing of fluid layers. The nature and fluid properties of the heat transfer fluids governs the type of geometric modification made in order to achieve heat transfer enhancement. Geometric modifications such as fins and corrugations are suitable for gaseous working fluid which have a very low convective heat transfer coefficient whereas, twisted tapes, wire coils, perforated discs, baffle plates and internally finned tubes are suitable for liquid working fluid which helps in creating turbulence which increases the heat transfer coefficient. However the use of geometric modifications and turbulators result in pressure drop that leads to more consumption of pumping power. Numerous researchers have carried out investigation on the effect of the use of geometric modifications on heat transfer enhancement. Few studies pertaining to heat transfer enhancement due to the use of turbulators is summarized in

Table 1. Bhagoria et al. [1] investigated the effect of wedge shaped transverse integral ribs used as artificial surface roughness on the heated wall (absorber plate) of solar air heater. The experiments were carried out for forced convection with Reynold number range 3000 – 18000, relative roughness height of wedge shaped rib 0.015 - 0.033, wedge angle of rib as 8°, 10°, 12° and 15°. They also developed a correlation for Nusselt number and friction factor in terms of geometric parameters of roughness elements and Reynolds number.

Table 1 Heat transfer enhancement using geometric modifications on the heat surface

Author	Year	Type of fluid	Shape	Configuration	Type of study
Bhagoria et al. [1]	2002	Air	Wedge shaped rib		Experimental study
Bhushan et al. [2]	2011	Air	Protrusion on plate		Experimental study
Karwa et al. [3]	2013	Air	Rectangular rib in v-down shape		Theoretical study
Lanjewar et al. [4]	2011	Air	W-shaped rib		Experimental study
Kumar et al. [5]	2009	Air	Arc shaped		Analysed using CFD

Bhushan et al. [2] carried out experiments to investigate the effect of protruded roughness on the heat transfer and fluid flow characteristics used for solar air heaters. It was found that the maximum increase in Nusselt number and friction factor was 3.8 and 2.2 respectively. Karwa et al. [3] carried out numerical study to evaluate thermal performance of solar air heater with V-down discrete rib roughness for space heating applications. Results of analysis were presented in the form of performance plots that could be used by designers to calculate desired air flow rate for different ambient temperature conditions and solar insolations. Lanjewar et al. [4] carried out experimental investigation on heat transfer and friction characteristics of rectangular duct roughened with W-shaped ribs on its underside on one broad wall arranged at an inclination with respect to flow direction. Range of parameters for this study were decided on basis of practical considerations of system and operating conditions. Correlations for Nusselt number and friction factor were also developed. Kumar et al. [5] analysed the performance of solar air heater with artificial roughness in the form of thin circular wire in arc shaped geometry. The Reynold number range was between 6000 and 18000. The overall enhancement was found to be 1.7.

III. NANO FLUIDS

Properties of the heat transfer fluid plays an important role in industrial heating and cooling applications. Thermal conductivity of the liquid is one of the vital physical properties that affects the performance of the solar thermal system. Thermal properties of liquids play a decisive role in heating as well as cooling applications in industrial processes. Thermal conductivity of a liquid is an important physical property that decides its heat transfer performance. Conventionally water, oil, ethylene glycol etc. are used as heat transfer fluids. In order to further enhance the thermal conductivity of these liquids, continuous attempts have been done by various researchers adding highly conducting solid. If the size of the solid additive is large, the particles would sediment, corrosion of system components may take place, clogging may happen and may also lead to excessive pressure drop. Thus the solid particles have to be in the order of nanometer. Nano fluids are therefore suspensions of nano particles of size smaller than 100 nm [6]. Small size and large surface area, less particle momentum, and high mobility are few features that make nano particles suspend in fluids [7]. The thermal conductivities of few solid additives with their base fluids is tabulated in Table 2.

Table 2 Thermal conductivities of solid additives with the base fluid [8]

Material		**Thermal conductivity (W/m K)**
Metallic solids	Iron	83.5
	Aluminum	237
	Gold	318
	Copper	401
	Silver	428
Non-metallic solids	Al_2O_3	40
	CuO	76.5
	Si	148
	SiC	270
	BNNT	200–600
	CNT (MWCNT)	3000
	CNT (SWCNT)	6000
Base fluids	Water	0.613
	Ethylene glycol	0.253
	Engine oil	0.14

Considerable research efforts and progress have been carried out in past decade to fundamentally understand the behaviour and effect of nano fluids. Few studies related to various aspects of nano-fluids have been presented below. Thermal performance of the evacuated tube solar collector with WO_3/Water nano-fluid was studied by Sharafeldin et al. [9]. The WO_3 nanoparticles were of 90 nm diameter. Three different volume fraction of WO_3 were considered. Results indicated that the efficiency of the evacuated tube solar collector was enhanced with more nanoparticles added. The efficiency of the evacuated tube solar collector reached 72.8%. Lin Lu et al. [10] carried out indoor experimental research to investigate thermal performance of high-temperature evacuated tubular solar collector using water-based CuO nano-fluids. Use of CuO nano-fluid increased the heat transfer coefficient by 30%. Bellos et al. [11] studied thermal enhancement of solar parabolic trough collectors by using nano-fluids and converging-diverging absorber tube. Three working fluids were investigated namely thermal oil, thermal oil with nanoparticles and pressurized water. A dimpled absorber tube with sine geometry was tested as the shape increased the heat transfer surface area and the turbulence in the flow. It was observed that the use of nano-fluids increased the collector efficiency by 4.25% while the geometry improvement increased the efficiency by 4.55%. Akhavan - Behabadi et al. [12] carried out experimental study to investigate heat transfer and pressure drop characteristics with heat transfer oil nano-fluid flow inside corrugated tubes. The results showed that tube corrugating shifted the flow regime to the turbulent condition at a lower Reynolds number. The highest enhancement in the heat transfer rate occurred at Reynolds numbers in which the flow inside smooth tubes was in the transition regime, where the corrugations make the flow to jump to the turbulent regime. Tsimpoukis et al [13] studies the performance enhancement of parabolic trough collectors using nano-fluids and turbulators. Results of the study showed that the use of nanofluids led to 0.76% enhancement of thermal efficiency, use of internal fins led to 1.10% increase and the combination of these techniques led to 1.54% enhancement of the thermal efficiency of parabolic trough collector.

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IV. Selective coating

One of the ways to maximize the harnessing of solar radiation is to use such a coating on the absorber surface which has high absorptivity and low emissivity so that it is able to retain the trapped solar energy. Coatings are classified into two types; selective and non-selective coating. For non-selective coatings, the optical properties such as absorptivity, reflectivity and emissivity are spectrally uniform. Thus the optical characteristic for such coatings is independent of wavelength over a particular range. Table 3 summarises experimental studies of few researchers with different solar selective coatings.

Table 3 Experimental studies on solar selective coatings

Author	Year	Substrate	Coating	α	ε	Technique used
Abbas [14]	2000	Nickel plated copper	Black chrome	0.96	0.12	Electrochemical treatment
Schuler et al. [15]	2000	Aluminium	a-C:H/Ti	0.876	0.06	PVD/PECVD
Farooq et al. [16]	2002	Copper and aluminium	V-Al2O3	0.98	0.02	Magnetron sputtering
Khamlich et al. [17]	2013	Tantalum	Cr/α-Cr2O3	0.90	0.28	Aqueous chemical growth
Céspedes et al. [18]	2014	Silicon and stainless steel	Mo–Si3N4	0.926	0.017	Magnetron sputtering

Abbas [14] carried out experiments to evaluate the effectiveness of solchrome solar selective coating. It was found that the use of solchrome solar selective coating which was a metal based coating increased the thermal efficiency of the solar collector by about 30% as compared to black paint. Schuler et al. [15] developed titanium containing amorphous hydrogenated carbon selective solar absorber coating for performance enhancement of solar collector. The optical properties were found to be strongly dependent upon the quantity of titanium along with few other parameters. Farooq et al. [16] developed a novel multilayer metal dielectric graded solar selective surface. Various selective absorbers were prepared by co-sputtering of metal and dielectric materials. Khamlich et al. [17] investigated the effect of annealing on the structural and optical properties of $Cr/\alpha\text{–}Cr_2O_3$ mono–dispersed particles based solar absorbers. Optical measurements showed that samples annealed above 400°C exhibited high absorbing optical characteristics than those annealed below 400°C. Céspedes et al. [18] developed a novel $Mo\text{–}Si_3N_4$ based selective solar coating for high temperature solar power applications. Solar absorptivity of 0.926 ±0.003, thermal emissivity of 0.017 at 25°C has been obtained. Analysis of thermal and optical performance of the present study on parabolic trough collector system yielded higher efficiencies as compared to existing selective coatings.

Conclusion

Present paper provides a comprehensive review of techniques to enhance the thermal performance of solar collectors. The outcomes of the review are summarized below.

- Geometric modification on the heated surface of the solar collector in the form of ribs, corrugations extended surfaces etc., enhances the thermal performance. Selection of a particular surface geometry modification depends upon the outlet temperature requirement, type of heat transfer fluid and the type of fluid flow through the solar collector.
- Use of selective coating on heated surface of solar collector increases its performance. Therefore there is need to develop cost effective method for producing solar selective coatings to be applied on absorber surfaces.
- Use of nano particles in the heat transfer fluid augments the heat transfer process and is an emerging area. The size of the particle, its volume fraction, type of heat transfer fluid, its pH value and type of flow are few important parameters that affects the performance of the collector.

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