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Multi-objective optimization of solar air heater with obstacles on absorber plate

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Abstract

A multi-objective optimization of a solar air heater with obstacles on an absorber plate is performed for maximum heat transfer and minimum pressure loss. In this work, shape optimization is carried out in conjunction with three-dimensional Reynolds-averaged Navier–Stokes analysis and two basic surrogate models: the response surface approximation and the Kriging models. Three geometric variables (the ratio of the obstacle height to the height of the duct; the ratio of the transverse pitch to the base length of the obstacle; and the angle of attack) were used as design variables for the optimization. The average Nusselt number and friction factor were used to define the two objective functions. The Latin hypercube sampling method was used to select the design points in the design space. A hybrid multi-objective genetic algorithm coupled with the surrogate model was used to find the Pareto-optimal solutions. The representative Pareto-optimal solutions were selected to study the trade-off between the two objectives. The response surface approximation model leads to a better set of non-dominated solutions over a wide range of functional space than the Kriging model. The optimization results show that the objective functions are significantly affected by the design variables, and the constructed surrogate models show good prediction accuracies for the objective functions. A performance factor was used to study the thermal–hydraulic performance of the Pareto-optimal solutions.

Keywords: Solar air heater; Obstacles; Thermal–hydraulic performance; Multi-objective optimization; Surrogate model; Reynolds-averaged Navier–Stokes analysis

1. Introduction

Solar air heaters (SAHs) have been widely used for energy conservation and management in an increasing number of installations. They are quite attractive for low-grade energy applications that require air temperatures below 100 °C (Close, 1963). Examples include space heating, dehydration of industrial products, and drying of agricultural crops such as vegetables, fruits, grains, spices, medicinal plants, lumber, tobacco, and fish. However, the conversion of solar radiation to thermal energy is generally poor in SAHs because of the inherently low heat transfer coefficient between the absorber plate and the air flowing through the duct.

Numerous methods to enhance heat transfer in SAHs are described in the literature (Varun et al., 2007; Wazed et al., 2010; Akpinar and Kocyiğit, 2010; El-Sebaii et al., 2011; Omojara and Aldabbagh, 2010; Alta et al., 2010). One of these methods is the introduction of obstacles in the dynamic vein of the collector, which create turbulence and thus enhance the heat transfer. Ozgen et al. (2009)

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Nomenclature

A_P	area of absorber plate (m^2)	p	pitch
b	base of obstacles (m)	P_l	longitudinal space between rows of obstacles (m)
C_p	specific heat of air (J/kg K)	P_t	transverse distance between two obstacles (m)
D_h	equivalent hydraulic diameter of the air passage (m)	P_l/e	relative obstacle longitudinal pitch
e	obstacle height (m)	P_t/b	relative obstacle transvers pitch
e/H	relative obstacle height	Q_{in}	rate of heat transfer to absorber plate
f	friction factor	Re	Reynolds number
f_o	friction factor for obstacle duct	T_f	average temperature of air (K)
f_s	friction factor for smooth duct	T_{ai}	bulk mean temperature of air at inlet (K)
h	convective heat transfer coefficient (W/m^2 K)	T_{ao}	bulk mean temperature of air at outlet (K)
H	duct height (m)	T_p	average temperature of plate (K)
k	thermal conductivity of air (W/m K)	U	Average velocity in duct (m/s)
L	test section duct length (m)	W	duct width (m)
$\dot{m}$	mass flow rate of air (kg/s)	W/H	aspect ratio
Nu	Nusselt number		
Nu_o	Nusselt number of the obstacle duct	*Greek Symbols*	
Nu_s	Nusselt number of the smooth duct	θ	angle of attack (°)
ΔP	pressure drop across the test section (Pa)	ρ	density of air (kg/m^3)

performed an efficiency evaluation of a new double-flow SAH with an absorber plate made of aluminum cans. The authors described energy and exergy relationships for different SAHs, and concluded that the irreversibility in the SAHs without obstacles is larger than those with obstacles. Esen (2008) presented experimental analyses of energy and exergy for a novel flat plate SAH with and without obstacles. He concluded that obstacles ensure good air flow over and under the absorber plates, create turbulence, and reduce the dead zones in the collector. Experimental investigation to determine the Nusselt number and friction factor for an arc shaped protruded roughened duct was carried out by Yadav et al. (2013). The correlations were also developed for Nusselt number and friction factor and the developed correlation were used for numerical evaluation of exergetic performance (Yadav et al., 2014).

Heat transfer to the flowing air can be increased by enlarging the absorber plate area of the SAH. However, increasing the area will increase the pressure drop inside the collector, accompanied by a substantial increase in power consumption to pump the air through the collector (Abene et al., 2004; Moummi et al., 2004; Kabeel and Mecarik, 1998; Karsli, 2007; Gao et al., 2007; Ho et al., 2009; Yadav and Bhogoria, 2014; Akpinar and Kocyiğit, 2010). Several investigations have been performed involving heat transfer enhancement inside SAHs using different shapes of obstacles such as metal mesh, a wedge shape, a V-shape, rectangular-shaped ribs attached to the absorber plate, and geometrical configurations (Saini and Saini, 1997; Bhagoria et al., 2002; Karwa, 2003; Tanda, 2004; Layek et al., 2007). Thermal performance of three sided artificially roughened SAHs with glass cover was made by (Prasad et al., 2014), the average values of friction factor and Nusselt number increases by 2–34% and 20–75% respectively as compared to the values of one sided roughened SAH and 150–200% more in terms of heat transfer than those of conventional smooth duct. In all the cases, it has been observed that the efficiency of a roughened SAH is higher than that of a smooth SAH. Experimental and numerical analyses of heat transfer augmentation in a rectangular duct with delta-shaped obstacles mounted on the absorber plate were performed (Bekele et al., 2013). The authors compared the heat transfer data with those for a smooth duct under similar geometrical and flow conditions, and reported that the obstacles mounted on the duct surface enhanced the heat transfer by 3.6 times compared to a smooth duct. A comparative study has been performed regarding SAH performances with various shapes and configurations of obstacles (Kulkarni and Kim, 2014). They found that a pentagonal obstacle shape produces the highest thermal–hydraulic performance among four different obstacle shapes of at Re = 6800.

Hegazy (2000) derived analytical criteria and proposed an equation for optimizing flat plate SAHs. He examined the effects of various parameters (flow rate, channel dimensions, absorber emissivity, and the wind heat transfer coefficient (HTC)) on the performance of SAHs, and suggested that a channel depth-to-length ratio on the order of 2.5×10^{-3} yields the best performance under the condition of variable flow operation. Studies on optimal thermo-hydraulic performances of artificially roughened SAHs have been reported (Chaube et al., 2006; Varun and Siddhartha, 2010; Prasad, 2013). SAH with integrated phase change material (PCM) storage has been designed and optimized by Summers et al. (2012). They have identified that a layer of 8 mm thick PCM (paraffin wax