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It is certified that the work contained in the thesis titled "**Novel Component Designs of Solar Energy Devices for Enhanced Thermal Performance**" by "**AJEET PRATAP SINGH**" has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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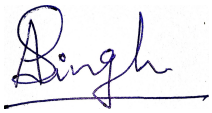
DECLARATION BY THE CANDIDATE

I, Ajeet Pratap Singh, certify that the work embodied in this thesis is my own bona fide work carried out by me under the supervision of Dr. Om Prakash Singh for a period of 3 years 11 months from July 2016 to June 2020 at IIT (BHU) Varanasi. The material contained in this thesis has not been submitted for the award of any other degree. I declare that I have faithfully acknowledged and given credits to the researchers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any others' work, paragraphs, text, data, results etc. reported in journals, books, magazines, reports, dissertations, theses, etc. or available at websites and have not included them in this thesis and have not cited as my own work.



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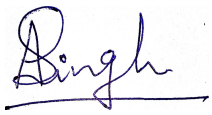

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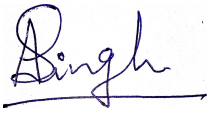

Ajeet Pratap Singh

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Nomenclature

A_c	Collector area (m^2)
A_p	Surface area of the absorber plate (m^2)
b_r	Width of quarter-circle groove (m)
b_t	Width of half-triangular groove (m)
b_{tp}	Top width of half-trapezoidal groove (m)
b_{tpd}	Bottom width of half-trapezoidal groove (m)
C_p	Pressure coefficient
ΔC_P	Streamwise differential pressure coefficient, $\frac{(P_t - P_b)}{1/2\,\rho V_\infty^2}$
C_{tp}	Total pressure coefficient
D_e	Equivalent diameter (m)
D_H	Hydraulic diameter (m)
D_n	Dean number
e_r	Quarter-circle groove height (m)
e_r/H	Relative quarter-circle groove height ratio
e_t	Half-triangular groove height (m)
e_t/H	Relative half-triangular groove height ratio
e_{tp}	Half-trapezoidal groove height (m)
e_{tp}/H	Relative half-trapezoidal groove height ratio
e_v/H	Relative V-groove height ratio
f	Friction factor
h	Convection heat transfer coefficient (W m^{-2} K^{-1})
H	Duct opening of solar air heater flow passage (m)
H_1	Width of the duct inlet opening (m)
H_2	Width of the duct outlet opening (m)
H_c	Chimney height (m)
h/R	Bell-mouth design ratio
I	Solar irradiance (W m^{-2})
k_a	Thermal conductivity of air (W m^{-1} K^{-1})
k_g	Thermal conductivity of glass (W m^{-1} K^{-1})
k_i	Thermal conductivity of insulation (W m^{-1} K^{-1})
L	Solar air heater duct length (m)
L_c	Characteristic length (m)
$\dot{m}$	Mass flow rate (kg s^{-1})
Nu	Nusselt number
P	Pitch of grooves (m)
P/e_t	Relative pitch ratio of half-triangular groove
P/e_{tp}	Relative pitch ratio of half-trapezoidal groove
P/e_r	Relative pitch ratio of quarter-circle groove
P/e_v	Relative pitch ratio of V-groove
ΔP	Pressure drop (N m^{-1})
Pr	Prandtl number

P_s	Static pressure at the location (Pa)
P_t	Total pressure at the location (Pa)
q	Heat flux (W m^{-2})
Q_u	Useful heat gain (J)
R	Bell-mouth curvature radius (m)
Ra	Rayleigh number
R_c	Curvature radius of the curved SAH geometry (m)
R_{ci}	Chimney inlet radius (m)
R_{co}	Chimney outlet radius (m)
Re	Reynolds number
t_c	Thickness of opening of the chimney (m)
T_i	Inlet temperature of air (K)
t_i	Thickness of the insulation (m)
T_o	Outlet temperature of air (K)
$T_s$or T_{pm}	Mean temperature of absorber plate (K)
V	Flow velocity (m s^{-1})
W	Width of the solar air heater duct (m)

Greek symbols

ρ	Density of air (kg m^{-3})
ρ_g	Ground reflectance
μ	Dynamic viscosity of air (N s m^{-2})
ε	Thermal effectiveness
ϵ	Emissivity
α	Absorptivity
τ	Glass plate transmisivity
ϕ	Curvature angle of curved solar air heater (°)
η	Efficiency
$\tau\alpha$	Transmittance-absorbent product of glass cover
θ_z	Solar zenith angle (°)
Υ	Surface azimuth angle (°)
Υ_s	Solar azimuth angle (°)

Subscripts

a	Ambient condition
∞	Freestream condition
$\circ$	Initial condition
g	Glass cover
i	Inlet section
o	Outlet section
p	Absorber plate
th	Thermal
θ	Angle of solar air heater w.r.t. horizontal plane (°)
θ_i	Solar radiation (insolation) inclination angle w.r.t. normal to the absorber plate of SAH (°)

Abbreviation

BM	Bell-mouth
CORR	Chimney outlet to inlet radius ratio, R_{co}/R_{ci}
CPSP	Curved plate single pass flow solar air heater

HSCPP	Hybrid solar chimney power plant
HTEF or EF	Heat transfer enhancement factor (Nu_{curved}/ Nu_{flat})
NuP	Nusselt number per unit pressure drop (Nu /ΔP)
MER	Mass flow rate enhancement ratio ($\dot{m}_{tapered\,with\,BM}/\dot{m}_{flat\,plate\,conventional}$)
PV	Photovoltaic
SAH	Solar air heater
SCPP	Solar chimney power plant
TER	Temperature enhancement ratio ($T_{o\,curved}$/ $T_{o\,flat}$)
TPP	Total pressure potential, N m^{-2}
TR	Collector taper ratio
WSC	Wedge shape collector

Abstract

The main focus of the PhD thesis has been to conceive and evaluate novel concept of bell-mouth and new collector design that can be easily integrated to solar energy devices such as solar chimney power plant (SCPP) and solar air heaters (SAH). Interestingly, both SCPP and SAH has common design components and work on the same natural convection principle. Both these devices have the following components: a solar collector and chimney. A novel concept of bell mouth inlet design, which reduces the losses significantly, has been developed and integrated to both SCPP and SAH and their thermal performance has been evaluated under various designs and environmental conditions.

Solar energy is a vast source of heat provided by the sun in the form of solar radiation, if utilized efficiently, can save millions of tons of carbon dioxide released by burning of fossil fuels. Sooner or later, the non-renewable sources of energy such as coal, diesel, petrol etc. would cease to exist due to excessive exploitation by human race. The only alternative would then be to develop efficient technologies to harness renewable sources of energy such as solar energy. Though solar energy is clean and available in abundance, it is not a concentrated source of energy like non-renewable sources of energy. One of the way to effectively use the solar radiant energy by redesigning of inefficient conventional solar energy powered devices. Among solar-thermal devices, solar chimney power plant (SCPP) is well known for electricity production and solar air heater (SAH) for air heating. Both works on the same principle: buoyancy driven mechanism. Though these clean energy powered systems are well established but their operational efficiency suffers owing to design limitations. A series of efficient novel designs of SCPP and SAH, with working fluid as air have been analyzed using experimentally validated CFD models. A combination of new concept of bell-mouth (BM) design inlet, converging collector flow channel and divergent chimney has significantly enhanced the power output by 9 folds. If multiple of such systems would be installed in the regions which are rich in sunshine, it can efficiently produce electricity to power almost thousands of villages. Further, this bell-mouth design was examined in conventional buoyancy-driven SAH with an objective to enhance the low hydraulic efficiency of the device. It was interesting to observe that the integration of bell-mouth design inlet significantly enhanced the mass flow rate of heated air. The high mass flow rates makes the device suitable for high flow rate applications. Secondly, the air temperature of the high flow SAH has been augmented by converging the parallel flow passage of SAH. Furthermore, a new convex and concave flow passage of naturally-driven SAH was designed and investigated for thermal performance. The energy and exergy analysis has been carried out for corrugated curved SAH. All the aforesaid new designs show significant impact in increasing the thermal and hydraulic performance of the solar-thermal devices. Lastly, a detailed aerodynamic analysis has been conducted to predict the real environmental wind impact on flat and curved SAH performance.

The chapter 2 explored the avenues to improve the electrical power output of conventional solar chimney power plant. As conventional sources of energy are depleting fast, solar energy based devices can only be mass adopted in future if suitable design innovations are conceptualized and investigated to improve its extremely low energy conversion efficiency. In this chapter, a series of new design concepts of solar chimney power plant are proposed and systematically investigated using an experimentally validated numerical model to maximize power generation capacity. A solar chimney consists two important components: a collector and a chimney. In a first, design of a third component called bell-mouth inlet with different orientation is proposed, investigated and optimized along with collector and chimney. Results show that with suitable design changes in collector, chimney and integrating an efficient bell-mouth at the inlet can increase the air velocity and hence turbine

output by about 270% compared to the conventional design. Physics behind such high increase in air velocity was also investigated. It is observed that total pressure potential or the static pressure recovery becomes high and uniform along the chimney height in the new design, which is entirely absent in conventional design. An uniform pressure distribution across the chimney height eliminates the recirculation zones thereby enhancing the system capacity to handle higher volume flow rates. Further analysis was conducted by scaling the lab-scale conventional model and proposed optimized design to a 50 kW power plant. Results show that the proposed new system can produce electrical power up to 1738 kW, which is about 35 times the conventional design can produce. The proposed design has the potential to meet the energy needs of thousands of villages.

The chapter 3 examines the possibility of integrating a photovoltaic (PV) module in a hybrid solar chimney power plant (HSCPP). Since HSCPP is a greenhouse thermal buoyancy-driven system, the surrounding high temperature environment makes PV module temperature extremely high resulting in lower electrical conversion efficiency. Various design configurations of collector duct and solar chimney are investigated using an experimentally validated numerical model to study the PV panel cooling and turbine power output. The results show that turbine power output is sensitive to diverging the chimney up to maximum static pressure recovery limit while PV module shows marginal increase in electrical efficiency. Converging the collector duct alone shows worst turbine and PV module performance. However, in case of combine designs of converging duct and divergent chimney, considerable improvement of PV panel efficiency (about 7%) was observed. The results show that about 80% of the collector area measured from the chimney axis are the most effective region for cooling the PV module where consistent temperature drop of 10-12 °C was observed. A design map vs. PV panel efficiency has been shown charting future directions for designing such energy efficient hybrid solar chimney systems.

Conventional natural convection flat plate solar air heater (SAH) suffers from low heat transfer characteristics. Putting extended surfaces in the air flow channel to augment thermal performance actually hinders the buoyancy driven flow, and thereby reducing the hydraulic performance due to high frictional losses. The objective of the chapter 4 is to enhance thermo-hydraulic performance by incorporating convex and concave flow channel with chimney effect. The curved SAH has been investigated using an experimentally validated computational fluid dynamic model for different curvature angles in the range of 25°-50°. The results show significant increase in Nusselt number per unit pressure drop (NuP), heat transfer enhancement factor, temperature enhancement ratio and effectiveness, in comparison to conventional flat SAH. The convex and concave designs are respectively 43% and 31% thermally, and 7% and 6% by NuP, higher than conventional flat natural convection SAH. Two different independent correlations derived for Nusselt number for different geometries were found to be in excellent agreement with the data. The designs and data presented in the study would help scientific community and solar based industries in developing efficient natural convection SAH.

Previous investigations have mainly focused on enhancing the thermal performance of a natural convection solar air heaters (SAH) at the expense of hydraulic performance by incorporating protruded surfaces and, thereby compromising on air mass flow rate significantly due to considerable pressure drop. Low mass flow rate of SAH makes it unsuitable for wide applications. In the chapter 5, design investigations using experimentally validated numerical model of SAH is reported that enhances flow rate by more than 100% in comparison to conventional flat plate SAH design. Integration of bell-shaped designs at the inlet of SAH adds to the ram-air effect that converts dynamic pressure into static pressure thereby manifesting into an excellent enhancement of air flow rate as well as in heat transfer associated with less hydraulic losses. The high-flow SAH was further investigated for building application using unsteady first-law of thermodynamic equation and it was observed to be 33% efficient over conventional design.

The bulk movement of fluid in natural convection solar air heater (SAH) is generated due to density variation and hence suffers from lower mass flow rates. Mounting additional surfaces/fins in SAH duct enhances the thermal characteristics, however, it comes at the cost of hydraulic performance. This limits the device usage in buildings and other high flow rate applications. In the chapter 6, two new designs of SAH were numerically analyzed are: (a) taper flow passage for better thermal performance; (b) tapered designs incorporated with bell-mouth inlet opening for improved hydraulic performance. Parametric design analysis was conducted for large range of taper ratio and bell-mouth ratio. The results show that the tapered design is about 70% thermally more effective and about 6% higher Nusselt number per unit pressure drop than conventional SAH. A significant enhancement in hydraulic performance of more than 300% was observed when bell-shaped inlet design was

integrated with the tapered designs.

In chapter 7, the investigation of various curved solar air heater designs has been reported. The promising design modifications proposed to further look for the avenues for thermal efficiency enhancement features. It was observed that secondary vortex formation near the absorber wall increases the Nusselt number significantly. New correlations for friction factor and Nusselt number has been developed as a function of Reynolds number and various geometric parameters such as relative groove height and pitch ratios for different design of air heaters. It is hoped that data of parameters i.e. Nusselt number (Nu), outlet air temperature (T_o), thermal efficiency (η_{th}) and friction factor (f) presented in this chapter would help researchers and industry in developing efficient designs of solar collectors.

Further, it has been observed that down-configurations of turbulators or extended surfaces on the flat plate solar collector significantly enhance the thermal performance. However, scientific literature on thermal performance investigations with down-configurations of ribs in curved SAH are rare. In the chapter 8, we systematically investigate using experimentally validated computational fluid dynamics model for different shapes of down-configuration of ribs. It was observed that half-trapezoidal and quarter-circular shape ribs shows maximum increase in thermal performance i.e. 17% and 16% , respectively, however frictional loss for quarter-circular ribs was observed to be less by about 10% when compared to trapezoidal shape ribs. The exergy recovery is maximum for trapezoidal and circular shape ribs and it is about 35% more than the smooth flat SAH. A new correlation has been developed for Nusselt number variation which has the form as $Nu = f\left[Re,\ \frac{e_r}{H}\right]$ where e_r is the height of quarter-circle groove. Observed data from the model matches well with the prediction from the developed correlation.

The chapter 9 evaluates and compares the performance matrix of a curved and flat solar air heater (SAH) under diverse environmental conditions using an experimentally validated numerical model. Firstly, the optimum curvature angle for curved SAH that offers optimum thermal performance (i.e. 25°) under wide range of parameters such as Reynolds numbers ($2200-6000$), mass flow rate ($0.0172-0.0472$ kg/sm^2) and solar radiation inclination angle ($0-60^\circ$) has been determined. The enhancement factor (i.e. Nu_{curved}/Nu_{flat}) is in the range $1.5-2.2$ which show that curved SAH is thermally much better than flat design. Secondly, the optimized curved SAH is then compared with flat design for 0 to 60° tilt angles (θ), under tranquil and windy conditions (wind velocity range:$0.5-4$ m/s), respectively. Under windy condition the heat loss from SAH to surrounding is lower for curved SAH at $\theta = 0^\circ$, 60° in windward, 30° in leeward and 30°in tranquil- condition in comparison to flat SAH. In the extreme case $\theta = 60^\circ$ and wind speed of 4 m/s, , the percentage change in average differential pressure coefficient ΔC_P is about 2% higher for curved SAH under windward while it is about 19% less in leeward condition compared to flat SAH.

A series of novel designs of solar-thermal devices have been investigated in the thesis with an objective to maximize the energy conversion for useful work. The efforts put in the present research is a small step towards the theme of *'**Let's go green to get our globe clean**'*.