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It is certified that the work contained in the thesis titled "**Study of Novel Designs of Solar Air Heaters for Enhanced Thermo-hydraulic Performance**" by **"AMIT KUMAR"** (Roll No.- 15131012) 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, Amit Kumar, certify that the work embodied in this thesis is my own bonafide work carried out by me under the supervision of Dr. Om Prakash Singh for a period of 6 years 6 months from July 2015 to December 2021 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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Amit Kumar

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Nomenclature

a	Absorption coefficient $\left(m^{-1}\right)$
A	Amplitude of wavy surface (m)
A_c	Cross-sectional area of duct $\left(m^2\right)$
A_{eff}	Effective area of absorber plate $\left(m^2\right)$
A/D_h	Relative roughness amplitude
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	Perimeter of duct (m)
C_p	Specific heat at constant pressure $\left(J/kgK\right)$
d	Rib diameter (m)
d/H	Relative roughness height
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
f	Friction factor
f/f_s	Friction factor enhancement ratio
g	Acceleration due to gravity $\left(m/s^2\right)$
G_b	Turbulent kinetic energy due to buoyancy $\left(J/kg\right)$
G_k	Turbulent kinetic energy due to mean velocity gradient $\left(J/kg\right)$
h	Convective heat transfer coefficient $\left(W/m^2K\right)$
H	Height of duct (m)
I	Solar irradiance $\left(W/m^2\right)$
k_a	Thermal conductivity of air(W/mK)
k_g	Thermal conductivity of glass(W/mK)
k_i	Thermal conductivity of insulation(W/mK)
L	Length of absorber plate (m)
$\dot{m}$	Mass flow rate $\left(kg/s\right)$
n	Refractive index of medium
Nu	Nusselt Number

Nu/Nu_s	Nusselt number enhancement ratio
P	Pitch of groove or rib or baffle(m)
P/e_r	Relative pitch ratio of quarter-circle groove
P/e_t	Relative pitch ratio of half-triangular groove
P/e_{tp}	Relative pitch ratio of half- trapezoidal groove
P/d	Relative arched baffle pitch
P/H	Relative roughness of pitch
ΔP	Pressure drop (N/m^2)
Pr	Prandtl number
q	Heat flux (W/m^2)
Q_u	Useful heat rate gain (W)
R_c	Curvature radius (m)
R_i	Inner radius of arched baffle (m)
R_o	Outer radius of arched baffle (m)
Re	Reynolds number
TF	Temperature factor
TI	Turbulent intensity
T_i	Inlet temperature (K)
T_o	Outlet air temperature (K)
T_m	Mean bulk temperature (K)
T_p	Absorber plate temperature (K)
T_{sky}	Sky temperature (K)
U	Mean velocity of fluid (m/s)
V_W	Wind velocity (m/s)
W	Width of SAH (m)
W/H	Aspect ratio of SAH

Greek symbols

$\alpha/90$	Relative baffle angle
α	Absorptivity
β	Curvature angle of SAH
ε	Thermal effectiveness
ϵ	Emissivity
λ	The wavelength of the wavy absorber (m)
μ	Dynamic viscosity (Ns/m^2)
η	Efficiency
ρ	Density of air (kg/m^3)
τ	Transmissivity of glass
ω	Solid angle

Subscripts

a	Air
c	Curvature
bm	Bulk mean temperature
∞	Free stream condition
g	glass cover
i	Inlet section
l	Lower channel
u	upper channel
o	Outlet section
p	absorber plate

Abbreviations

SAH	Solar air heater
TKE	Turbulent kinetic energy
SPSAH	Single-pass solar air heater
DPSAH	Double pass solar air heater
CDPSAH	Counter double -pass solar air heater

Abstract

Solar energy is a vast source of thermal energy. If utilized efficiently, it can save millions of tons of carbon dioxide released by burning fossil fuels. Sooner or later, the non-renewable sources of energy such as coal, diesel, petrol etc., would not be replaced due to excessive exploitation by the human race, Which will undoubtedly create problems for humanity. One of the most alternative ways would be to develop efficient technologies to harness renewable energy sources such as solar energy. Though solar energy is clean and available in abundance, it is not a concentrated energy source like non-renewable sources of energy. One of the ways to effectively use solar radiant energy by upgrading the designs of underperforming conventional solar energy powered devices. Solar air heater (SAH) is simple in construction, less bulky, and has lower production costs among solar-thermal devices. It is used for air heating. This hot air is utilised for space heating and drying agriculture products. Though solar air heaters are well established but their operational efficiency suffers owing to design limitations and lower heat transfer coefficients between heated surfaces and working fluids. To overcome aforementioned limitation of SAHs, the four performance enhancement techniques such as (1) Flow duct design, (2) configuration of absorber plate, (3) arrangement of fluid flow in the duct (parallel and counter), and (4) Shape of cross-sectional channel; are incorporated in the present work. Consequently, a series of efficient novel designs of SAHs, with working fluid like air, has been analyzed using experimentally validated CFD models. First of all, to enhance the convection heat transfer from the heated surface to the working fluid, the different geometrical ribs (Half-triangular, Half-trapezoidal and Quarter-circle) were attached with absorber plate in the down configuration of curved SAHs. The best shape of the rib (Quarter-circle) was determined based on the thermohydraulic performance. In second studies, fluid flow is divided into two channels (upper and lower) in a parallel configuration, utilising two types of ribs (circular and semicircular) in curved SAHs. After investigating their performance, the best location of the absorber plate in the duct (i.e., at the center between glass and insulating wall) and the shape of ribs (semicircular) are observed. Utilizing the previous knowledge transforming the best design of parallel curved double pass solar air heater (DPSAH) into counter curve DPSAH for further enhancement of performance. After observing the deficiencies of counter curve DPSAH, further studies were performed by utilizing backwards arched baffles in the lower channel to increase convection heat transfer from absorber plate to air. Lastly, the effect of the shape of cross-sections (rectangular, triangular, trapezoidal and semi-ellipse) on the performance of SAHs also presented. Further, this best cross-sectional shape SAHs was examined with a sinusoidal wavy absorber. All the aforesaid new designs show significant impact in increasing the thermal and hydraulic performance of the solar air heaters.

Recent investigations reveal that curved solar air heaters (SAH) thermo-hydrodynamically performs better in comparison to flat SAH design. 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 chapter 2, 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 $Nu = f[Re, e_r/H]$where e_r is the height of quarter-circle groove. Observed data from the model matches well with the prediction from the developed correlation.

Recent research has also shown that flat plate double-pass solar air heaters (DPSAH) exhibit higher thermal performance compared to conventional flat plate single-pass solar air heaters (SPSAH). However, scientific literature on design and performance evaluation of a curved DPSAH is scarce. In chapter 3 , we systematically investigated various designs of DPSAH and reported its performance characteristics using a validated numerical model. Higher outlet air temperature by about 5°C was observed when the DPSAH absorber plate is located at the mid of the insulating wall and transparent glass cover. Furthermore, putting asymmetric semi-circular roughened surfaces shows better performance than symmetric circular shapes as the reattachment of vortices with the absorber plate is more frequent in the former case. Two new correlations were developed for Nusselt number (Nu) and friction factor (f) as a function of Reynolds number (Re) and relative roughness height (d/H). The values of Nu and $f$obtained from the developed correlations agree well with data from the model.

In chapter 4, a novel design of counter flow curved double-pass solar air heater (DPSAH) is proposed, and its performance characteristics are numerically investigated and compared with various parallel designs under different flow and geometric conditions. The developed model is first experimentally validated. The hydraulic and thermal performance of various DPSAH designs (smooth curved single pass, smooth parallel curved double-pass, smooth counter curved double-pass, roughened parallel curved double-pass, and roughened counter curved double-pass) show that counter flow curved DPSAH with asymmetrically placed turbulators is thermally better compared to other designs. A maximum of 23% augmentation in thermal performance was observed. To predict the performance of the best design, new correlations for Nusselt number (Nu) and friction factor (f) are developed in terms of Reynolds number (Re) and relative roughness height (d/H). The data estimated from these correlations are in good agreement with the values of f and Nu predicted from the model.

The aim of chapter 5, is to numerically investigate a new curved design of a counter flow double-pass solar air heater with arched baffles placed in the second duct. Due to high inertia of the flow and curved nature of the design, fluid in the second channel tend to move away from the absorber plate and thus, reduces the thermal efficiency significantly. In order to overcome this deficiency, new design parameter is introduced in the second duct in terms of arched baffles and their design is optimized for various geometric parameters such as angle of attack, variable pitch ratio etc. for best thermo-hydraulic performance. It was observed that arched baffles accelerate the flow near the absorber and facilitate the formation of large secondary vortices that enables multiple attachment zones at the absorber plate. Enhancement in thermal and hydraulic performances are discussed in terms of flow visualization, local Nusselt number, thermal effectiveness and friction factor ratio. The maximum enhancement of Nu in roughened curve CDPSAH with baffle angles $\alpha/90 = 0.5$ at P/d =6 are found in the range of 20-28%, higher than without baffles. Moreover, two new regression correlations are developed for prediction of thermo-hydraulic performance in terms of geometrical and flow parameters.

Rising future energy demands can be met with solar-based devices such as solar air heaters (SAH) only if the efficiency of these devices is enhanced with suitable design changes. Flow channel design of a SAH is an essential aspect for enhancing its thermo-hydraulic performance for a wide range of Reynolds numbers. In chapter 6, a systematic approach has been adopted to investigate various non-rectangular channel designs numerically, and results are compared with the conventional rectangular design. The energy input to all designs is kept constant. The channel design that gives the best performance was further investigated by incorporating a sinusoidal wavy absorber having variable wavy roughness parameters. The flow and heat transfer characteristics have been evaluated in terms of friction factor (f) and Nusselt number per unit friction factor (Nu/f), temperature factor $(T_o-T_i)/I$, thermal effectiveness (ε), Nusselt number (Nu). The results show that the SAH duct having a semi-ellipse cross-section offers the best thermo-hydraulic performance and has maximum augmentation in temperature factor of about 10% compared to conventional SAH. Moreover, semi-ellipse SAH with sinusoidal wavy absorber has a maximum value of f/f_s and Nu/Nu_s at $A/D_h = 0.12$ and $\lambda/D_h = 0.8$ for the range of Reynolds numbers used. Here, A is the amplitude and λ is the wavelength of the absorber plate. New empirical relationships for Nu and f are established as a function of flow and geometric parameters that agree well with numerical results.

A series of novel designs of solar air heaters have been investigated in the thesis using computational fluid dynamics with an objective to attenuate reliance on fossil fuels. The efforts put in the present research certainly adds contribution to the global theme of ***'Let's go green to get our globe clean'***.

The primary environmental benefit of installing the proposed designs of SAH is to provide hot air using solar energy. Solar energy-based appliances do not harm our environment and human health. It is today's leading cause; people prefer solar energy-based equipment to meet

and save their energy demand and expenditure, respectively. The hot air ($37-80°C$) produced from these devices has a significant role in numerous thermal (moderate and low) applications such as providing heat to buildings heating, distillation, agricultural and industrial drying of products, such as cocoa, coffee beans, fruit, noodles, rubber, or some seafood items. The temperature requirement for crop drying application may be about $45-70°C$, which could be easily satisfied by installing the proposed design of SAHs. Moreover, the hot air of these SAH can be used to heat the room or building during the winter seasons. It will save energy consumption used by HVAC devices and is most suitable where electrical energy is scarce. The manufacturing of any equipment depends on its simplicity of designs, cost of making material, smooth and noiseless operation, high thermo-hydraulic efficiency, reliability, wide acceptability and feasibility. Conventional manufacturing processes follow (1) design, (2) prototypes, (3) testing and (4) mass production. During this process, chances of failure, investment and repeatability are more. Due to overcome these disadvantages, therefore in modern manufacturing process follow: (1) design, (2) applied the computed aided engineering, (3) prototypes, (4) testing and (5) mass production. Based on the discussed concern, numerical work presented in this thesis shows that the proposed designs of SAHs have higher thermal performance than conventional SAH and full fill all the requirements of manufacturing. Therefore manufacturing of these SAHs must be procced in industry.