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A Review on the Use of Vortex Generators in Solar Air Heaters: Experimental Insights and Theoretical Models for Performance Improvement

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ABSTRACT

This review investigates the use of vortex generators (VGs) in solar air heaters (SAHs) to enhance thermal performance and efficiency. Vortex generators, as passive elements, disrupt airflow to promote turbulence, thereby improving heat transfer and mitigating inherent inefficiencies in traditional SAHs. The review consolidates experimental findings and theoretical models to evaluate the influence of various VG configurations, such as delta-winglets and perforated ribs, on convective heat transfer. Insights into the role of parameters like geometry, pitch ratio, and placement are provided, highlighting their effects on thermal and hydraulic performance. Computational Fluid Dynamics (CFD) simulations are emphasized as a pivotal tool in analyzing fluid dynamics and optimizing VG design. Challenges like balancing pressure drops, material degradation, and scalability are explored, alongside potential solutions through hybrid systems and advanced design methodologies. Future research directions are outlined to address economic viability and long-term reliability, emphasizing the integration of VGs into more adaptive and modular SAH systems. This study underscores the critical role of innovative VG technology in advancing solar heating solutions to meet sustainability goals.

1. Introduction

The increasing international need for energy and the undesirable influence of fossil fuels on the climate has enhanced the search for renewable resources. Solar energy is one of the safest forms of energy, though SAHs are quite uncomplicated technologies to convert solar energy into thermal energy that can be used for heating purposes. While complex solar water heating systems are used, SAHs employ low-cost materials and simple structures, therefore more applicable.

SAHs work based on capturing solar thermal energy on a surface which heats up the air passing through or over it. These heated airs is useful in space heating in residential as well as commercial buildings, drying of agricultural produce, and curing of building materials. They are ideal to build since their designs do not involve complex structures and hence require little maintenance. However, challenges with thermal efficiency are evident in the traditional SAHs.

Studies show that despite the low cost of the materials used in SAH, and the simplicity of construction, they suffer from low convective heat transfer coefficients between the airflow and the absorber surface. This inefficiency results from some properties of air as a heat transfer medium, hence poor transfer of heat. Therefore, to increase the efficiency of SAHs, it is necessary to increase heat transfer rates within SAHs.

Thus, integrating of VGs in SAH designs is among the prospective directions to address the

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problem. VGs are simple devices situated in the heater ducts where the variable patterns of airflow are adjusted so as to provide increased turbulence and therefore, mixing. This turbulence enhances convective heat transfer coefficients and at the same time provides reasonable pressure gradients across the system.

Several investigations have examined different types of VG such as ribs, baffles and winglets, with a view of determining the effect of these features on thermal performance of various SAH geometries. Research results indicate that the placement and design accurately determine the heat transfer enhancement and flow resistance.

While more research is carried out on SAH with vortex generator technology, the need to create more reliable methods of experiment and theoretical methods for the prediction of performance under varying operating conditions. By increasing the understanding in this field, researchers seek to enhance the implementation of VGs into current systems, placing solar heating solutions on par with conventional fossil fuel-based solutions, [26], [28], [10], [25], [17], [22], [6] and [4].

2. Fundamentals of Solar Air Heater Systems

2.1 Basic Principles of Solar Heating

Solar air heating is also a renewable energy technique that uses solar radiation in order to cause heating of air. It transmits direct sunlight to heat, thus improving climate control for buildings and industries. The system uses the absorber material which has high absorptivity of the incident radiation and which may be black in color. Incident light falls on the absorber surface that in turn radiates heat to the cooler adjacent air.

The warmed air finds a variety of uses such as in space heating for residential, commercial and industrial use and in drying of agricultural produce. Solar air heaters have low energy consumption from fossil fuels; however, the efficiency of the solar air heaters depends on the tilting angle of collector, material choices, surface area and weather condition.

There are two main types of solar air heaters: glazed and unglazed collectors. Heated models: glazed, are applied to space heating because of the ability to retain heat; they consist of an insulated box with glass on top. Transpired solar collectors or unglazed collectors are used where insulation is not a major requirement.

For improvement of thermal efficiency, one or more of the configurations may be used, including fins or baffles to optimize contact between the air and the heated absorber or vortex generators that promote air mixing and heat transfer.

An advantage of solar air heaters is due to their simplicity and lower manufacturing costs than liquid systems and no freezing problem associated with liquid transport fluids. However, their thermal efficiency is considerably low because of the low density and heat carrying capacity of air. They can produce usable heat during some of the sunny times, but fail in the colder months when the need is highest.

Integrating solar air heaters with other technology gives rise to the photovoltaic-thermal hybrid systems, combining electricity and thermal systems at once. All these systems must therefore be designed in ways that accommodate for both these functions.

Current research activities also seek to enhance the capability of solar heater designs through simulations and experimental approaches in as pertaining to materials, configuration and cost. A study of the basics of solar heating creates a foundation prior to examining superior boosts in its efficiency, [5], [34], [26], [15], [22], [6], and [31].

Figure 1. The front façade of this building is a transpired solar air heating system that heats the incoming ventilation air for the facility, [26]

2.2 Components of Solar Air Heater Systems

The design of solar air heating systems is anchored on the following key components that form the framework of converting solar energy to heat. In the middle of these systems is the solar collector, which is an important piece of equipment that has to be able to efficiently collect solar radiation. This collector most often has a transparent cover through which sunlight can be allowed to penetrate while avoiding heat loss. It is normally fashioned from glass, polycarbonate or even low-emissivity glass that in turn, greatly boosts its functionality. Under this cover, there is the absorber plate, which is typically made of high absorptance materials such as aluminum, or copper, which are a key to achieving high heat absorption.

In these systems, air is used as the working fluid and passes over or through the absorber plate to take heat. The construction of the air ducts also plays a critical role; it is constructed with the appropriate dimension and material to form the needed airflow characteristic and enhance heat transfer performance. Materials used to make these ducts are aluminum, steel and occasionally, strong plastic products that allow efficient transfer of heat.

In as much as configuration is concerned, the number of duct designs in solar air heaters is diverse. These can be as simple as a flat-plate collector to a manifold collector can or corrugated plate collector etc. Both designs are intended to provide uniform airflow distribution over the absorber surface and at the same time, a turbulent flow is desirable for increased convective heat transfer coefficient compared to laminar flow.

One of the most important components of the protection of the energy accumulated in the system is insulation. Most commonly used in the back and sides of the collector, insulation reduces conductive and radiative heat loss, which can substantially reduce the efficiency of the collector. In some designs, double-glazed fronts can also be provided to minimize heat loss still further.

In addition, it is known that some of the more sophisticated solar air heater designs provide their duct systems with vortex generators. These devices are still installed in a controlled manner to generate turbulence in the airflow significantly increasing the mixing, thereby increasing direct heat exchanger thermal efficiency.

Therefore, the efficiency and sustainable reliability of a solar air heater depend on every facet of the design including the collector design and materials used. When these components are optimized together, the objective of the researchers is to enhance the cost efficiency as well as the energy yield in solar air heating systems [21], [21], [15], [22], [6] and [23].

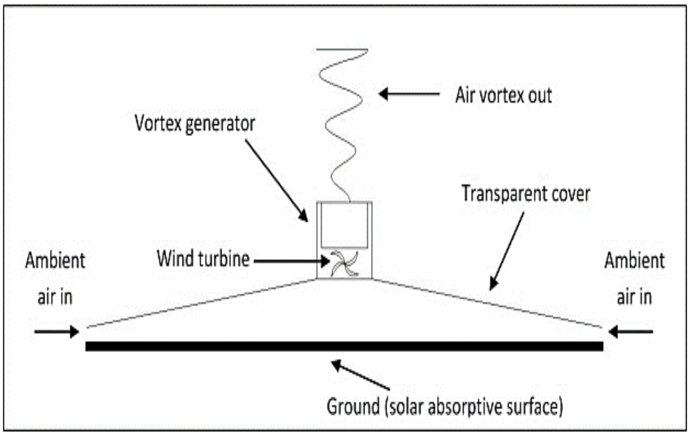

Figure 2. Fundamentals of solar vortex engine for power generation, [2]

Table 1: List of various testing standards of solar collectors and their recommendations, [23]

Test procedures and standards	Year	Recommendations
CSA F 378.2 Standard	2011	● In this approach, the reference temperature is temperature of the inlet air. ● These air heaters should be used under open to ambient and closed loop conditions. ● This is largely based on ANSI/ASHRAE 93 standard, although there are differences, including added functional test information, incident angle modifier, collector time constant, and additional reliability tests. ● The F378.2 standard promotes the integration between the "ASHRAE Standard 93" and "EN 12975-1, 2" approach.
National Bureau of Standards (NBS)	1974	● It is also required that the airflow measured by airflow measuring apparatus should not be more than ±1.0% of the total airflow. ● The static pressure drop of through the solar collector is measured using a manometer with a precision of 2.49 N/m^2. ● Time measurements and mass measurements shall be made to an accuracy of ± 0.20 % as specified herein. ● The pressure taps shall comprise nipples of 6.4 mm welded to the duct and fitted over holes of 1 mm diameter. ● No tests are recommended for the collector time constant and the angle modifier of the incident radiation.
ASHRAE Standard 93	2010	● This is limited to collectors that have one effective inlet and one effective outlet. ● In the test that are done to find the incident angle modifier the orientation of the collector should be ± 2.5° of the incident angle being used in the test. ● In order to achieve a negative pressure gauge in the collector, it is recommended that the blower be installed downstream of the collector. ● When used in a pressurized condition, the blower may be positioned upstream of the collector. ● In calculating the efficiency, the gross frontal area of the collector is applied rather than the aperture area

Test procedures and standards	**Year**	**Recommendations**
FSEC Standard 102-10	2010	● The static pressure shall be measure after the exposure test and before the thermal efficiency test. ● Flat cover plates of all types of construction shall be of non-shattering or tempered variety. ● Taking down condensation using desiccant is permitted. ● It should also be evident that penetration of moisture should not adversely affect the structure and performance of the collector. ● Deformation or corrosion is said to be severe if the functioning of the collector was impaired or if there are signs that degradation is in progress.
ISO 9806	2017	● For solar air-heating collectors, the following tests are suggested: the rupture test, the collapse test, and the assessment of the optimum start temperature. ● In many subsystems, collectors with polymeric materials and the working fluid are in intimate contact and the rate of leakage under stagnation conditions needs to be defined. ● It is suggested that the leakage rate should be assessed for the conditions of ambient temperature and absence of radiance. ● First, the time constant must be determined since it will significantly reduce the time effort in testing as well as eliminate potential failure in testing.
EN 12975-1,2	2006	● Ambient temperature (ta): the value of this parameter should not exceed ±1.0 K in case of indoor testing, or ± 1.5 K in case of outdoor testing. ● The changes in inlet temperature of the collector should not be more than ± 0.1 °C for the steady state process and should not be more than ± 1 °C for quasi-dynamic state test method.

Figure 3. Photograph depicting the test equipment from an experimental perspective, [13]

2.3 Operating Mechanisms and Efficiency

In solar air heater systems, the processes that take place play a great role in determining its efficiency. Integral to this process is the collector that is used to trap solar energy aimed at warming air that passes through it. These systems’ design and configuration are critical to thermal efficiency. The essential part is the absorber plate, while other parts are the various flow patterns that can improve heat transfer.

A notable approach of the enhancement is the incorporation of vortex generators, which significantly enhance thermal-hydraulic characteristics. These devices affect the laminar boundary layer close to the absorber surface by inducing vortices that enhance convective heat transfer between air and the absorber plate. This mixing effect minimizes the thermal resistance to allow energy absorption to take place more effectively.

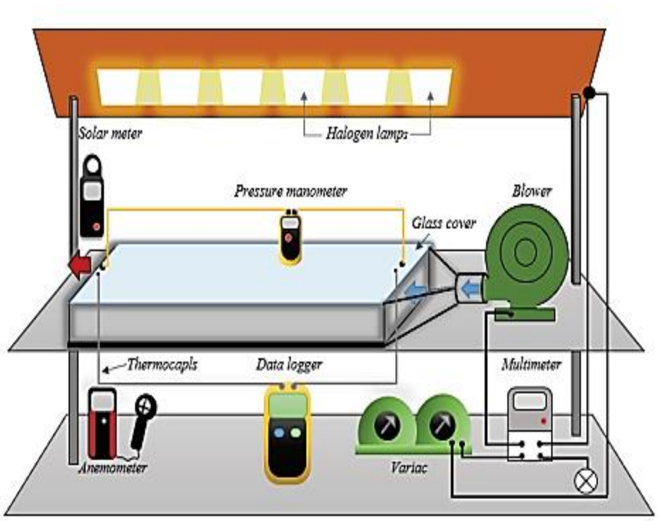

Figure 4. Illustration depicting the structural layout of the experimental perspective, [13]

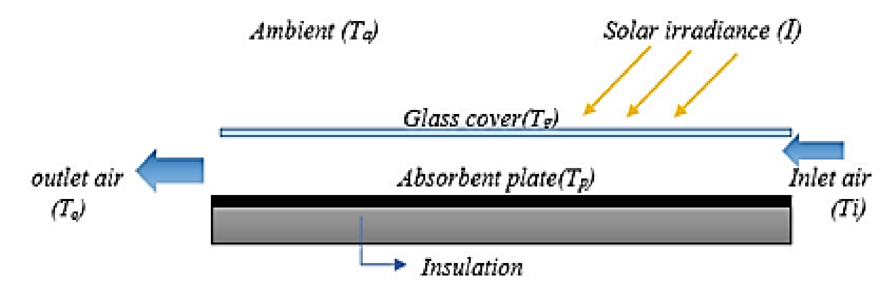

Figure 5. Single pass SAH, [13]

Several parameters can influence the effectiveness of the SAHs, which include the flow rate, the temperatures and geometry of the system. Research has shown that by raising airflow rates, the thermal performances are likely to benefit; but this leads to higher-pressure drops all over the system. Actually, work at a velocity and pressure loss that offers the greatest possible productivity.

These numerical simulations are useful in explaining the effects of design parameters on performance indicators including Nusselt number and skin friction factor under Reynolds numbers. It has been found out that, when certain vortex generator geometries are placed particularly ends of channels for instance rectangular or delta types or others, there are marked enhancements in Nusselt numbers over those arrangements not containing such features.

It is therefore possible to conclude that integration of corrugation on plates with vortex generators offers an efficient method of enhancing heat transfer rates as well as the system. These configurations are reported in empirical research to not only increase turbulence but also to keep pressure drops to acceptable levels thereby increasing thermal characteristics of the system without a compromise on the mechanical properties.

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Furthermore, it is possible to fine-tune the parameters of a certain technological tool, e.g. the angle of attack for the vortex generators, greatly influencing their efficiency. Some angles have been found to provide the most performance improvements with regard to turbulent kinetic energy profile across the collector channels. This goes to show the need for specialized designs depending on the result of a numerical analysis.

Therefore, the recognition of these operational mechanisms provides a fundamental understanding for the improvement of design strategies that may further improve the thermal efficiencies in SAHs with vortices. As new material technology and computational methodology for modeling the fluid flow in such systems continue to improve in future, definite higher level of efficiencies can be expected with reasonable operating cost.

3. Vortex Generators: Design and Working Mechanism

3.1 Types of Vortex Generators

The vortex generators are important features in the solar air heaters with the specific function of improving the heat transfer rate. They work through the prevention of the airflow; they generate vortices that enhance the mixing process in addition to the convection heat transfer coefficient between fluid air and the absorber surface. Different kinds of vortex generators have been designed, and every one of them has different structures that affect its characteristics.

Most popular type includes delta wing vortex generator having cross-sectional shape of a triangle. This shape is especially good at ‘locking in’ to the low-pressure region which in turn is able to produce high vortices at small angles of attack. Delta wing vortex generators can be placed on or approximately the absorber plates, proving most advantageous when used in applications which involve fluctuating flow velocities and where prompt thermal interchange is necessary.

Other important shaped vortex generators are rectangular and trapezoidal ones. For a variety of reasons, it is often better to have a rectangular flow that will provide an even spread of vortex along the length of the flow, which will improve the mixing over a larger area. Trapezoidal vortex generators are a cross between rectangular and delta designs, and their general performance is a compromise between the two; they offer less drag but less mixing depending on the configuration.

Variations on traditional shapes include those with holes within them, for example, the Perforated Delta Wing Vortex Generator (PDWVG), which reduces pressure loss while, at the same time, maximizing heat transfer. These innovations permit increased airflow velocities through the system passage, enhanced thermal efficacy without gross augmentation of energy demand.

Transverse vortex generators have received much attention because they could provide much larger potential for thermal augmentation compared to longitudinal designs such as Longitudinal Vortex Generators (LVGs). The orientation direction of the LVGs that generate a continuous vortical flow that aligns with the direction of the airflow maintains optimum turbulence levels at very low-pressure drop.

Randomized evaluations reveal that various arrangements produce diversified impacts on parameters such as Nusselt number, pressure drop, and overall thermal efficiency. For example, the proper learning of angles of attack for these devices can enhance thermal-hydraulic performance—frequently even beyond a flat surface.

Some of the parameters that affect vortex generators’ performance include; height, the distance between the components, the distance between successive generators or the pitch ratio and geometries that are made to suit specific applications. Changes towards these parameters allow an engineer to design heat exchanger system in response to anticipated heat exchange operating conditions and/or obtain the required levels of heat transfer.

Published studies have also illustrated that applying more than one sets of vortex generators at selected locations in a solar air heater can help optimize most of the performance parameters through better turbulence intensity over wider surface area

and a lesser temperature differential leading to higher heat transfer rates.
This diverse type and design allows the researcher and the engineer to understand the advance convective process and design new effective solar air heater systems with efficient vortex generation techniques for harnessing the energy from the sun more effectively, [2], [9], [7], [1] and [3].

3.2 Design Parameters Influencing Performance

In the context of designing VGs for solar air heaters, many important design factors affect the performance and effectiveness of the devices. Features of the geometrical design of the vortex generator are also critical and encompass dimensions such as length, height, and other sizes and shapes of the component. These geometrical factors play a very significant role in the generation as well as sustenance of vortices in the flowing air. For example, longitudinal vortex generators (LVGs) are more effective than transverse ones because the former create stronger and more stable vortices while at the same time experiencing lower pressure losses in terms of heat transfer.
The angle of attack is yet another parameter; with this angle effectively altered, it is possible to make substantial modifications of the flow around the generator and thus the heat transfer rates. Numerous investigations have revealed that suitable filming angles can further intensify turbulence and upgrade the mixing of air in the heater channel. For instance, the study finds that a delta wing-style VG placed at particular orientations can produce TEF of 1.8 to 2.1 under certain circumstances.
Furthermore, the spacing between multiple VGs or the pitch ratios also offer an important influence to the two-way interaction and downstream flow characteristics. Optimization of the transverse pitch ratio improves the thermal characteristics while minimizing hydraulic losses.
Another area of importance concerning the enhancement of heat transfer efficiency is surface modifications on VGs. Other surface modifications such as creating perforations or holes on the VG surface can also distort the airflow patterns; although their design is complex because of the conflicting effects on the pressure loss and heat transfer coefficients. Hole diameter and placement analysis shows that indeed, the friction factors are substantially reduced by perforations but the effectiveness of the vortex must not be sacrificed in the process. The kind of materials used to make VGs may also influence performance results in some certain parameters like thermal conductance and roughness of the walls, critical for heat transfer.
Furthermore, the location of VGs in the heater system should be properly designed; VGs should be located along the flow paths for better performance without compromising significantly the airflow rate due to high-pressure drops.
This paper therefore gives an insight on how these design parameters affect solar air heater systems that incorporate vortex generators. There is an increasing amount of experimental data in conjunction with computational studies offering new information on optimized VG designs for improved thermodynamic efficiency in solar heating, [2], [10], [9], [8] and [14].

4. Experimental Studies on Vortex Generators in Solar Air Heaters

4.1. Overview of Experimental Methods Used

Several methods are employed in experimental studies of vortex generators in SAHs to determine their thermal characteristics and effectiveness. One of them is to use solar simulators that provide controlled lighting conditions allowing implementing accurate measurements of temperature gradients and airing flow in the heater. Conventionally, halogen lamps are employed to mimic solar conditions, and the magnitude of power is controlled to attain various extents of intensity, 330-850 W/m^2. Such a systematic setting enables the researcher to determine the impact of various vortex generator arrangements on heat transfer rates.

The often used approach is to incorporate the artificial roughness elements directly into the design of the SAH. For example, delta-winglet vortex generators and ribbed structures can be evaluated in single pass and double pass arrangements. In these tests, the height ratio of roughness to the wavelength is held constant at about 0.6, whereas other factors such as, pitch ratios and angle of attack are changed. This approach allows for systematic examination of how various design decisions affect thermal performance and convective heat transfer.

Such experiments depend on the Reynolds number, which in most of the studies varies within a range of about 5,000 – 14,000 to simulate the transitional flow situations realistic to practical applications. Temperature distributions are measured at these flow rates and are used to calculate mean bulk temperatures for comparison with baseline (smooth) geometries.

However, some works include a more rigorous analysis by adding higher-order statistics or CFD computations with experimentation. These simulations offer a comprehensive description of the fluid flow behaviour within the heater duct and offers explanation for the interactions produced by multiple vortexing effects.

To capture the right performance parameters, standard instrumentation comprises of thermocouples installed at various points along the absorber plate and at discrete locations in the ducting network. Pressure sensors may also be used to measure the friction losses arising from greater levels of turbulence generated by vortex generators.

Likewise, most researchers pay equal concern on the multi-objective optimization approaches at the time of conducting experiments to understand the impact of various design parameters on the general performance results. This consists of further testing whereby the five ribs dimensions, the spacing configuration and the positions of the vortex generators with respect to the ribs are tested and compared against efficiency measures such as the thermal efficiency and the friction factor ratios.

The findings of each work greatly help in developing new and enhanced designs of SAH to yield better heat transfer coefficients by the use of vortex generators or roughness elements. Thus, systematic experimentation is very important for further improvements in knowledge in this field, [4], [3], [13], [18] and [6].

4.2. Results and Observations from Key Studies

It has emerged from the experimental studies that incorporation of VGs in solar air heaters resulted in enhancement of thermal parameters and efficiencies. Different types of the vortex generators have been examined in this regard analysing their impact on heat transfer characteristics. For instance, Al-Kayiem et al. conducted a performance assessment of three dissimilar vortex generator configurations by CFD simulation with specific reference to the intensity and stability of air vortices. In their results, they pointed out that previous studies mainly focused on quantifying air velocity and temperature within the system; however, CFD provided a further understanding of the nature of air vortices outside the system.

The researchers also pointed out that the simple square vortex generators yielded different performance levels compared with other designs including cone structures or with perforations. The basic design (Case-1) was taken as reference for performance and Case-2, which had a cone structure, provided better stability to the airflow that in turn enhanced thermal efficiency. In Case-3, the hole in the vortex generator was made smaller to enable more detailed elaboration of the interactions between the airflow and the heating surfaces.

Besides the case studies of Al-Kayiem et al., other experiments suggested that changing rib angle and surface roughness, as the design parameters, could enhance the heat transfer rates. Specifically, studies revealed that the enhancement of heat transfer coefficients realized by incorporating broken transverse ribs on an absorber plate was mainly due to the promotion of turbulence within the airflow that is essential for improving thermal performance.

In addition, the integration of the external recycle systems with the vortex generators has also been made. In double-pass solar heaters with corrugated absorber surfaces, the researchers noted that using an external recirculation technique could enhance thermal efficiency by increasing the velocity of the fluid in the collector channels. This synergy resulted in a higher convective heat transfer coefficient, and this means that operational settings are as crucial as structural modifications.

The other research undertaken was the effect of mass flow rates on thermal characteristics. Some studies determined mass flow rates where thermal efficiency achieved its peak but beyond these values led to lower efficiency due to high-pressure drop and increased energy demand for pumping which reduces total exergy efficiency of the system.

Furthermore, comparative studies of various forms of solar air heater systems indicated that the manner and degree of performance improvement depended on the selected vortex generator configurations and operational conditions. Some geometries obtained high thermodynamic efficiencies in certain Reynolds numbers and thereby suggested that optimization of these parameters is important for the enhancement of solar heaters.

In conclusion, insights derived from these varied experimental studies demonstrate a consistent trend: proper vortex generator can provide good improvement in heat transfer rate and overall system performance through favorable flow dynamics and optimal thermal mixing patterns of the fluid in SAHs, [23], [19], [24], and [2].

5. Theoretical Models for Solar Air Heater Performance with Vortex Generators

5.1. Mathematical Modelling Approaches

Mathematical modelling therefore plays an important role in analysis of thermal behaviour of solar air heaters with vortex generators. Different mathematical models estimate the system’s performance and reliability, considering heat transfer kinetics, flow rate, and other aspects. One of the common methods for mathematical modelling of heat exchangers is based on the energy balance equations that reflect such phenomena as the interaction between the flow and heat exchanger surfaces.

Various types of models are used in this study. Lumped parameter models suppose that the temperature is constant throughout the system while one-dimensional (1D) steady state and unsteady state models show changes in temperature along the flow paths with time. These models can be deduced from first axioms or observed from actual measurements.

As for the ODEs arising from complex heat transfer situations, approximate solutions through finite difference technique or numerical integration are used. These models are easily implemented by software tools inclusive of MATLAB and are also employed to process solutions arising from these models.

Computational simulations are a function of boundary conditions, turbulence models and model simplifications among others. The agreement of density values with experimental density data is important for checking the accuracy of the results. Comparisons between the experimental data and the computed values of temperature rise of air indicate that the present analytical models for double and triple pass solar air heaters are accurate where critical parameters such as mass flow rates and inlet temperatures are taken into account.

Furthermore, advanced modelling typically employs exergy analysis in order to determine the quality and efficiency of energy in addition to Balance of Energy equations. This approach does not only quantify energy transfer but also the quality of that transfer in terms of usefulness or heating.

It can therefore, be concluded that Computational Fluid Dynamics (CFD) has emerged as a sound means of simulating solar air heaters with vortex generators. It reflects the fluid flow patterns more accurately than most conventional computational techniques, which give better estimations of pressure drops and velocity distribution. With several turbulence models, the vortex generators can be designed for the improvement of mixing and rate of heat transfer.

In totality, mathematical modelling is a critical tool in the development of solar air heater that provides accurate performance prediction under different weather conditions while providing design direction through validated theoretical frameworks, [11], [6], [2] and [17].

5.2. Validation against Experimental Data

This paper is aimed at the verification of theoretical models for solar air heaters incorporating vortex generators with the experimental data that is decisive for appropriate validation of predictive simulations. This is usually done by comparing the results of the simulations of mathematical models or CFD with those from practical tests. This approach has been used in many studies showings that models with reliable probability estimates can accurately reproduce observed thermal performance metrics.

For example, a study on a triangular channel solar air heater used a verified mathematical model to estimate the thermal efficiency and outlet air temperature. The results obtained have revealed a decrease in predictive error, which ranges from 25 to 50% of the standard energy balance equations to demonstrate the capacity of the model for capturing the dynamics of the system and its components during various conditions of operation. In addition, this study investigated various mass flow rate with the conclusion that there are definite settings that give maximum performance outputs which are nearly equal to experimental values.

Another case may be studied in conjunction with experimental and numerical investigations of jet-impingement solar air heaters with transverse ribs on the absorber plate. This configuration was benchmarked using a theory exclusively designed to its configuration and the performance data of this configuration were found to match the generated theory curves. This involved evaluating the effects of airflow rate of the air mass on thermal efficiency arising from turbulence created by ribs.

In addition, vortex generators have been researched for their application as devices that enhance flow fields in solar air heaters. Probably the most significant example of the study's usefulness was its validation of CFD simulations through experimental airflow velocities measurements at different points of the system. More particularly, when comparing the results of the tests on basic and cone guide designs of the vortex generators with the results of the simulations, the differences between prediction and measurement values did not substantially exceed 1.9% in terms of the percentage of velocity rise throughout all the designs. These results offer valuable evidence for the numerical precision and real value of the CFD simulation in terms of actual application.

A validation process may call for a number of factors that would back statements relating to model efficiency. Many of these works have presented overall performance attributes including Nusselt numbers and friction factors obtained from the experimental configurations to add strength to theoretical analysis. In particular, coefficients have exact matching of modelled performance characteristics with experimental ones for different configurations and working conditions.

Further, the enhanced mathematical modelling that incorporates the fluid-solid interaction shows enhanced thermal performance of the system with the flexible vortex generators incorporated in the double pass solar air heaters. Analysing the experimental results, it was found that considerable improvements over the conventional designs are achieved, thus supporting the numerical simulations and the positioning of the vortex-generating appendages.

Thus, the verification of the theoretical models with respect to empirical data lays the important groundwork of continuing to improve the current and future methods of design used in SAHSs with VGs, [2], [17], [14], [20] and [6].

Table 2: Validation results of the CFD procedure based on the vortex generator performance in accelerating the air velocities, [2]

Case	CFD Percentage of velocity increase in the vortex generator	Exp. Percentage of velocity increase in the vortex generator	Percentage of relative error in the velocity change
Case-1 Basic design	90.4 %	88.7 %	1.9 %
Case-2 Cone guide	90.9 %	89.3	1.76 %

6. Influence of Vortex Generators on Heat Transfer Enhancement

The incorporation of VGs in SAHs is well understood as a very promising technique to increase heat transfer efficiency. All these smartly designed gadgets disrupt the airflow, and thus the laminar boundary layer that in most cases hinders effective heat transfer. By providing for turbulent flow, VGs facilitate the mixing of cool incoming air with the hot air near the absorber plate leading to high convection coefficients and thus minimal thermal resistance.

Delta winglet and multi V shaped rib designs are some of the VG designs, which have shown a great promise in enhancing thermal performance. Studia show that delta-winglets enhance the Nusselt number by 3,5 times compared to the plain plates or even a smooth surface. This improvement is attributable to the ability of the winglets to create vortices that accelerate the fluid mixing and improve the interaction with the surface.

Due to the mechanical action of VGs on the airflow it is possible to observe the complicated change of the flow field in ducts of solar air heaters. These devices promote swirling motions which in turn generate secondary currents or recirculation zones which in turn erode the thermal boundary layers. This kind of effects develops locations where heat transfer between the absorber plate and air is optimized, as well as the general thermal efficiency.

These findings are further backed by empirical investigations reflecting a much-improved thermohydraulic performance when VGs are applied. For example, studies of configurations with different arc forms or with gap structures determined that the convective heat transfer coefficients are higher than the conventional smooth surfaces. One of the studies showed that if baffle-type vortex generators were installed then turbulence intensity in SAH channels increased and overall heat transfer characteristics were enhanced.

VGs design parameters are rather sensitive and their optimal values should be correctly set depending on the application in solar air heaters. Geometry of the duct system specifically height, spacing and shape of the ducts has a direct effect on the generation and maintenance of vortices. CFD simulations have proved useful in determining effects of these parameters on flow and thermal characteristics under various operating conditions.

Furthermore, findings demonstrate that incorporating different VG designs, for instance wavy grooves with vortex generators, have an even more enhanced heat transfer due to the increased level of turbulence. This is a unique approach that avails optimized capacities of different forms of VG.

The use of VGs may also address the problems of pressure drop that are usually experienced when turbulence is increased for the same improvement in thermal performance. As vortices enhance the boundary layers through their paths, negative pressure effects associated with traditional roughness techniques for heat transfer enhancement are partially addressed.

In total the use of vortex generators in SAHS increases the convective heat transfer by increase the turbulence while also has possible ability of the numerous applications on space heating industrial processes and other usages of solar energy technologies [10], [32] and [10].

7. Thermal and Hydraulic Performance Analysis

Thermal and hydraulic performance of solar air heaters with vortex generators are explained in the work in question by showing how these aspects improve heat transfer while staying within reasonable pressure drop limits. Vortex generators delay the occurrence of laminar boundary layer and enhance turbulence that leads to better heat transfer and constant temperature distribution on the absorber plate, enhancing overall heat conversion efficiency.

A great many studies have supported the notion of the ability of vortex generators to improve the thermal efficiency as experimental investigations suggest that flows through systems equipped with these devices exhibit higher Nusselt numbers and therefore higher heat transfer coefficients. A transition of flow characteristics from laminar to turbulent and an overall enhancement of thermal transport processes is observed when vortex generators are used especially at higher Reynolds numbers.

From a hydraulic standpoint, the primary issue is the optimization of heat transfer with a trade-off of pressure loss. Most vortex generators are bound to enhance the frictional losses due to the disruption of the streamlined flow. Scientists express pressure drops in various arrangements and relate them to enhancement in heat transfer, to achieve the best thermo-hydraulic performance factor (TPF), including effectiveness along with acceptable pumping power boost.

Specifically, comparative evaluation studies reveal those different configurations of the vortex generator impact thermal and hydraulic performance in divergent ways. There are also some complex designs like the staggered position or the winglets which truly alter the flow patterns and increases only a small amount of pressure loss.

Numerical and wind tunnel tests are performed in parallel in a number of experiments to provide a detailed assessment of design features. CFD offers understanding of flow characteristics, useful to locate positions and sizes of vortex generators corresponding to the particular collector configurations and conditions, enabling modifications to increase thermal performance and hydraulic safety.

The thermal output and pressure variation greatly depends upon the operational parameters such as mass flow rate, ambient temperature and collector tilt angles. Literature shows that under the best circumstances, there is a potential for increased heat transfer coefficients and overall system effectiveness. In general, the appropriate consideration of the effects of vortex generators in the flow of fluid continues to be critical in avoiding energy losses while focusing on improving the performance of the flow to minimize pumping energy linked to [5], [11], [23] and [27].

8. Comparative Review of Different Vortex Generator Designs

Design of vortex generators has evolved, especially in solar air heaters. Different designs, shapes and orientation affect heat transfer rates and flow patterns in a big way. Delta winglet vortex generators are peculiar for the enhancement of turbulent flow near hot stripes; and they demonstrate the best aerothermodynamic characteristics in comparison with standard rectangular ones in the range of laminar and transitional Reynolds numbers.

Curved trapezoidal winglet vortex generators have been found as a suitable substitute, which performs better in turbulent situations and has better thermal efficiency since these wings provide stable vortices that promote mixing in the boundary layer without losing pressure. Triangular and rectangular vortex generators are also used; The triangular shape is preferable at higher angle of attacks while the rectangular types provide satisfactory results in various conditions. The comparative analysis indicates that in the context of specific applications triangular configurations can produce lower drag forces.

Optimising conical vortex generators also indicate considerable thermal enhancement factors with new TEF, changing flow characteristics, minimising drag, and achieving high temperature differences at the heated surfaces. There is a growing trend towards the use of multiple vortex geometries, evidence that shows that using other shapes or configurations such as V-baffles enhances the heat transfer rates and hence improves the airflow and heat management systems in solar air heaters.

Using performance metrics, the role of geometry—shape and orientation—in the effectiveness of the vortex generators is established. Features like edge cutting on the rectangular winglets further improve the flow field and minimizes thermal boundary layers. Moreover, the configuration of the transverse or longitudinal pitches in the vortex generator rows may also improve thermal performance with minimal hydraulic penalties.

These designs require experimental methods and CFD simulations to provide better understanding of the interactions of the airflow. Using CFD in parallel with physical prototype validations advances the prior arts for better solar air heater systems. New trends are integration solutions that can be adjusted after the installation which gives a clue to the trend towards more flexible energy technologies. Subsequent performance evaluations of the vortex generator design further establish the geometric characteristics – functional performance relationship and contribute to the development of energy solutions for specific context, [2], [16], [8], [33] and [10].

9. Challenges and Limitations

This paper was undertaken with an aim of establishing various problems associated with the application of vortex generators in solar air heaters in order to enhance their efficiency. One such issue is the ability to increase heat transfer efficiency while also maintaining reasonable pressure drops throughout the system. Although these devices cause the generation of turbulence and augmentation of the heat transfer coefficient, there are also associated penalties of frictional pressure drop that could offset the thermal gains. To maintain such balance, pressure drop considerations must be integrated into design aspects during the pipe system design.

Another consideration relates to the shape of the vortex generators: their geometrical arrangement. It has been realized that slight differences in the shape, size and angle of deploying the sheets can lead to big changes in their performance. Thus, adjustment of these characteristics is essential, but it is challenging because of the complex flow physics. Also, the variations in the performance of vortex generators from one operational condition to another like changes in airflow rates or temperatures may also be a hindrance to the expansion of the variety of designs used in the present study.

Fluctuations in solar energy collection rates combined with limitations on the solar air heaters restrict the utilization of vortex generators even when in use. These systems depend on solar irradiance and, therefore, energy is available constantly; therefore, thermal output experiences changes with the day and seasons. In conditions of low irration or adverse climate the efficiency of these systems can be considerably reduced; therefore, additional heating is sometimes required, which can lead to additional expenses and higher energy consumption.

The second potential problem is material degradation over the product's useful life when used in solar air heater systems with incorporated vortex generators. Since the heaters are exposed to environmental conditions and may be affected by UV radiation, moisture corrosion, among others, the entire heater assembly, including accessories such as vortex generators, can also be affected. The costs of maintenance and possibly replacements should also be incorporated into long term management plans.

Therefore, economic aspects are also relevant when assessing sophisticated elements such as the vortex generators of solar air heaters. Controllable fixed costs might rise as installments because the initial setup of new designs would call for the use of complex know-how processes or expensive equipment. Ways that could prolong the return of investment may include; If the enhancements do not result in corresponding levels of improved efficiency than what simpler options could provide.

In terms of scaling up, some designs may not translate well from experiments in a lab or simple use in real-life situations because the flow pattern in larger installations is quite different. As a result, observations that researchers make from such experiments may not be accurate in determining results of large-scale research projects.

Last but not the least, there is some lack of standardization; different measurements are used to evaluate the outcomes, which makes it difficult to compare different research activities and to spread the usage of higher-quality practices on different areas or between various territories. Adoption of standard testing procedure would go a long way in harmonizing the results and more especially enhance positive advancement in this technology field.

Such challenges call for further research in the matter pertaining to improvement of the vortex generators with respect to the cost and the environmental performance of the solar air heating systems, [10], [32], and [30].

10. Future Directions and Research Needs

The study on vortex generators in solar air heaters is still an unexplored research area which shows significant potential because of increasing need for better thermal performance and energy efficiency. Further research should be aimed at the design of more advanced vortex generators that can be used in different conditions and which ensure the greatest interference of the air flow to achieve the maximum turbulence and convective heat transfer. Consequently, fundamental parametric studies are critical to evaluate the effects of design parameters such as size, shape, angle, and location on thermal performance at various Reynolds numbers.

Further enhancements in the complexity of the CFD simulations combined with the real-world experiments give a richer understanding of the specific designs of vortex generators and the resulting air flow. They include capability predictions pertaining to the structure's behaviour under different conditions, which prove useful during design. However, applying machine learning methods can find the best configuration by studying experimental data from previous experiments.

The economic feasibility and the environmental impacts of the new vortex generator technologies must also be assessed. Thus, cost-benefit analyses will distil how these innovations can be introduced without substantial costs in the existing systems. Moreover, evaluating the reduction in CO2 emissions associated with efficiency improvement is acceptable by sustainability standards internationally.

Another interesting area is the combined use of the vortex generators and some other heat transfer enhancement techniques. Further research studies could look into the synergy between the turbulence increasing features like the rib turbulators with the total system functionality, and may show other manners of achieving increased thermal efficiency without significant compromise to pressure drop penalties.

The literature also requires the implementation of case studies that evaluate the solar air heaters efficiency with vortex generation in different climates. Long-term surveys will give data on the life cycle, required service and dependability of the machines in the course of their use.

It is important to approach some issues connected with the increase in scale of the advanced solar air heater systems, such as reduction in the cost of manufacturing, as well as striving to meet the set quality standards. Studying non-integrated progressive constructions could improve system flexibility as technology advances by exploring designs that allow for equipment update.

Such interdisciplinary collaborations as engineers, material scientists and environmental scientists will help drive innovation in this field. Hence, by incorporating various forms of knowledge within a multidisciplinary team, researchers can define comprehensive tactics for the enhancement of SAHs with vortices, applying these tactics to the simultaneously improvement of efficiency and environmental impact, [29], [23] and [30].

11. Conclusion

The integration of vortex generators in to solar air heaters is a valuable innovation in improving thermal performance and the efficiency of the system. Numerous experimental and theoretical investigations have indicated that the use of vortex generators is capable of changing the nature of flow within the heater channel to enhance heat transfer coefficients. Some of the literature studies point out that the level of enhancement obtained for a particular flow depends on the design of the vortex generators, including winglet and rib configurations. In this regard, design factors including the angle of attack and spatial arrangements have been identified to have profound impact on both the thermal efficiency and pressure loss across the system.

When incorporating vortex generators, the turbulence level in the airflow is raised and this enhances mixing and the temperature pattern on the absorber’s surface is improved. These enhanced interaction between the air and collector surface helps in minimizing thermal losses at the same time, enhance heat gaining from the solar radiation. Results suggest that it is possible to achieve significant augmentation of Nusselt numbers and thus, convective heat transfer coefficients, when using particular configurations as compared to conventional designs without such additions.

Still, there are many questions about the best way to use the advantages of vortex generators to raise performance and the reliability of the devices under changing situations. Future research should therefore aim at achieving these two objectives in a manner that does not create high pressure drops that spurs increased pumping costs. However, more detailed research based on the durability of such systems in various regions of the world that experience varying climatic conditions will be required to support the effectiveness of these systems.

The importance of advanced modelling techniques cannot be overemphasized; performance forecasting requires sound theoretical models in different operational conditions. These models should be further defined so that they would not only reproduce experimental outcomes but also facilitate the assessment of new design enhancements.

Therefore, the implementation of vortex generator technology in solar air heating systems signal a right step in the direction of increasing energy efficiency, which is critical if renewable energy is to gain more acceptance. This line of thinking re-emphasizes the global sustainable development goals by providing efficient engineering solutions to energy demands without using fossil fuels, [28], [25], [12], [27], [11], [4], [23] and [10].

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