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Heat Transfer Rate Intensification Using Kite Vortex Generator with Punched Hole

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Abstract **-** Air solar heater performance is much dependent on the efficiency of heat transfer process between its absorber plate and air. This could be achieved by improving the flow distribution in through the plates. Therefore, in this simulation study, kite vortex generators with punch holes (KVGH) were used to improve the flow distribution as well as enhance the heat transfer rate. The thermal-hydraulic performance of KVGH is evaluated using a range of attack angles (θ = 30°, 45°, and 60°) and hole diameters (d = 2mm, 4mm, and 6mm) for Re = 5000 to 25000. This work has investigated via numerical simulation a total of nine cases. The simulation results indicate that the average Nusselt number and friction factor are significantly higher than the channel without KVGH (smooth channel). As a result, the inclusion of KVGH has significant implications, particularly for improving heat transfer rates. In terms of thermal-hydraulic-performance (THP), the case with attack angle θ = 45° and d = 2mm achieves the highest value of THP= 1.29. For all attack angles, the highest average THP = 1.26 is achieved for hole diameter d = 2 mm, and the highest average THP = 1.25 is achieved for attack angles of 45° at all hole diameters. The results indicate that for all Reynolds numbers, an increase of 30°, 45°, and 60° in the attack angle corresponds to a 24.73%, 31.26%, and 31.46% increase in the Nusselt number, and a 6.78%, 11.53%, and 14.72% increase in the friction factor, respectively. For all Reynolds numbers, an increase in the diameter of the punched hole by 2mm, 4mm, and 6mm results in a 30.62%, 28.95%, and 27.87% decrease in the Nusselt number, and an 11.93%, 10.77%, and 10.33% decrease in the friction factor, respectively.

Keywords**:** Heat Transfer Enhancement, Vortex Generator (VG), Thermal-hydraulic Performance (THP), Nusselt Number

1. Introduction

Rapid technological and economic advancements drive the demand for energy consumption. Energy resources are mainly classified into renewable and non-renewable energy. The substantial use of energy in economic activities is causing the depletion of finite natural resources and the release of greenhouse gases, particularly carbon dioxide (CO_2) [1]. Due to the gradual depletion of non-renewable energy sources, it is imperative to explore and discover alternative renewable energy options. In response to this issue, researchers have turned their attention to solar energy as a viable renewable energy alternative[2]. Consequently, researchers have undertaken various studies and developments in order to maximise the utilisation of solar energy in a wide range of applications [3]. The applications of solar air heaters involve the utilisation of solar energy. However, these applications have faced challenges in terms of inefficient thermal energy transfer. The primary resources of solar air heater applications are solar energy, which has been subjected to inefficient thermal energy transfer as a result of the poor convective heat transfer coefficient between the air and the absorber plate [4, 5]. In order to generate turbulence and disrupt the boundary layer, numerous researchers have identified methods to address this challenge, including the use of double-pass air heaters, packed or porous bed absorber plates, ribs, artificial roughness on absorber plates, and fins. This approach results in improved heat transfer performance [4]. In order to optimise heat transfer efficiency, researchers have investigated two prevalent methodologies: active and passive. In an effort to enhance the convective heat transfer coefficient, vortex generators (VGs) have been extensively investigated as passive heat-transfer enhancement devices [6]. The fundamental principle of VGs is to generate secondary flow, specifically longitudinal vortices (LVs), which can disrupt or detach the thermal boundary layer that has formed along the wall [7]. This process involves the transfer of heat from the wall to the core of the flow through the use of large-scale turbulence [7]. The presence of a hole has been found to have positive effects, as it reduces flow resistance and minimises pressure loss. In contrast, the absence of a hole leads to high pressure loss because the vortex generator (VG) acts as a blockage [8].

2. Numerical Simulation

This study utilises the geometry for the kite shape proposed by [9] and the geometry for the channel proposed by [2]. The governing equations, initial and boundary conditions, can be found in greater detail by referring to the work of Demirag [2]. The Shear Stress Transport (SST) k-ω turbulence model has been selected for this study. The pressure-velocity coupling was resolved through the utilization of a semi-implicit method for pressure-linked equations consistent (SIMPLEC) algorithm. The QUICK scheme is employed to implement the discretization of convective terms. The computations are considered to be convergent when the residuals of all the equations are within 10^{-5}, except for the energy equation, which requires a residual within 10^{-6}. Monitoring residuals is not the only criterion employed in the convergence process. Moreover, it has been observed that the surface area-weighted average heat transfer coefficient and temperature value remained constant from one iteration to another, indicating a consistent trend.

In order to ensure the accuracy of numerical solutions, a grid independence study has been conducted for the channel with a kite vortex generator with punched hole (KVGH) with an attack angle of 30° and a 2 mm hole diameter at 7 different tetrahedral cell numbers: 76834, 242290, 455565, 575035, 707339, 822387, and 964043. Based on the observed deviation rate of less than 1% in Nu, it can be inferred that increasing the element number to 707339 would not be advantageous, as the solution does not show any significant changes with respect to the element number. Thus, the value 707339 has been chosen to ensure grid independence. The experimental results of [2] are used to validate the current numerical simulation, which is considered the baseline model, by utilizing the channel without a vortex generator at Re=2500. The numerical solution also validated with Dittus-Boelter and Gnielinski correlations. Based on the numerical solution, Nu demonstrate a strong agreement with the experimental data, Gnielinski and Dittus-Boelter with an average mean deviation of 6.74%, 8.16%, and 13.54% respectively.

3. Results and discussion

Following determination of the optimal number of grids in the computational domain and validation of the numerical model, the effect of attack angle, θ and punched hole diameter, d on KVGH is investigated. The simulation results of attack angle, θ and punched hole diameter, d variations are compared to the smooth channel, evaluating *Nu* and *f* within the range of Re = 5000-25000.

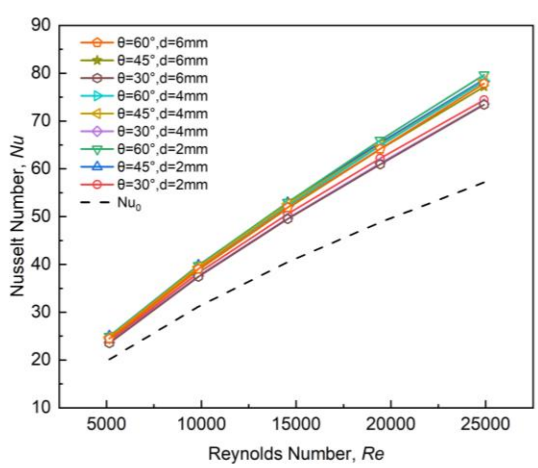

Fig. 1: Influence of KVGH attack angle, θ and punched hole diameter, *d* on *Nu* against *Re*.

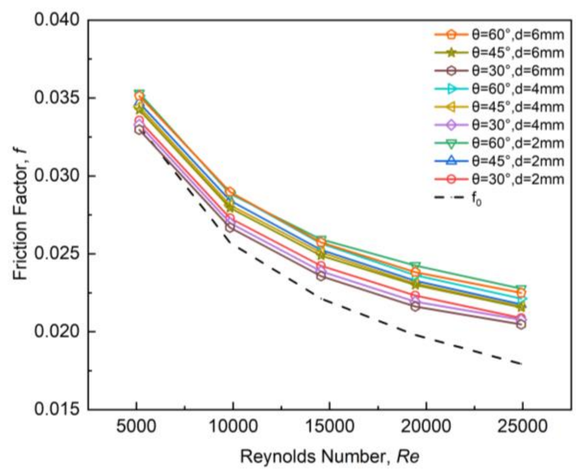

Fig. 2: Influence of KVGH attack angle, θ and punched hole diameter, *d* on *f* against *Re*.

Figs. 1 and 2 illustrate the variation of the simulated results for *Nu* and *f* values of smooth channel and KVGH with varying attack angles ($\theta = 30°, 45°, 60°$) and punched hole diameters ($d = 2\text{mm},\ 4\text{mm},\ 6\text{mm}$). At all attack angles, the Nusselt number is determined to increase in conjunction with an increase in Reynolds number, as is the case with smooth channels. The reason for this is that the thermal boundary layer on the surface is disrupted by increased turbulence, which is a result of higher flow velocities [2]. This will eventually facilitate improved mixing between hot and cold fluids that are present on the surface wall, thereby increasing the rate of convective heat transfer [10]. In contrast to smooth channels, the presence of KVGH with a variety of hole diameters and attack angles leads to the formation of longitudinal vortices. The Nusselt numbers increase significantly in comparison to smooth channels at all Reynolds numbers numbers as a result. The Darcy friction factor, f, for the smooth channel and the channel with KVGH at $\theta = 30°, 45°, 60°$ and punched hole diameters of $d = 2$mm, 4mm, 6mm is plotted against the Reynolds number in Fig. 2. The f value decreases as the *Re* increases across all attack angles and punched hole diameters, as illustrated in Fig. 2. When comparing a smooth channel to a channel equipped with KVGH at various attack angles and punched hole diameters, the f value is significantly lower. The presence of KVGH within the channel posed as an obstacle to the air flow, resulting in a notable increase in the friction factor. The various hole diameters and attack angles of the KVGH force the airflow to navigate through the narrow holes. The flow constriction leads to the formation of larger low-pressure zones behind the KVGH [2]. This, in turn, causes an increase in pressure loss and friction.

The effect of punched hole diameter and attack angles for KVGH on THP is presented in Figs. 3 and 4, respectively. Based on the figures presented in Fig. 3, it can be observed that the THP value increases with an increase in *Re* for each punched hole diameter. The results indicate that the highest THP is observed when $d = 2$mm, in comparison to $d = 6$mm, for all *Re*. For all *Re*, the highest and lowest THP values are obtained when using the smallest and largest punched hole diameters, respectively. When the diameter of the hole is increased, it allows for a greater amount of flow to pass through the hole. This results in the creation of a jet flow, which reduces flow resistance and leads to a decrease in pressure loss. Nevertheless, the jet flow and secondary flow have been found to have a significant impact on the longitudinal vortices produced by the KVGH, leading to disruptions in flow mixing and disturbances in the thermal boundary layer [8]. When the diameter of a punched hole is smaller, there is a notable decrease in flow passing through the hole, leading to a significant pressure loss and an increase in pressure at the back of the KVGH [8]. However, this also results in a weaker jet flow compared to a larger diameter, and it does not have a significant impact on the longitudinal vortices or secondary flow. Thus, smaller diameters have a greater impact on heat transfer compared to hydrodynamic performance, resulting in higher THP values at all *Re* values. The KVGH with the highest THP value and an attack angle, $\theta = 45°$ outperforms others at all *Re* values, as illustrated in Fig. 4. The thermal boundary layer development is more effectively disrupted when the attack angle of the KVGH is increased in comparison to a lower attack angle [2]. This effect, however, reaches a plateau beyond 45°. An additional increase in the attack angle results in a greater amount of flow blockage, which constricts the airflow passage and creates a low-pressure region behind the KVGH [8]. As a result, an 45° attack angle appears to provide an optimal balance between thermal and hydrodynamic performance, which leads to improved THP across all *Re*.

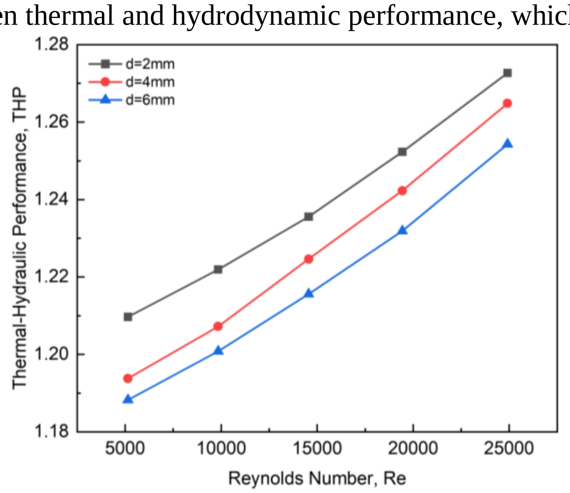

Fig. 3: The effect of punched hole diameter, d on THP against *Re*.

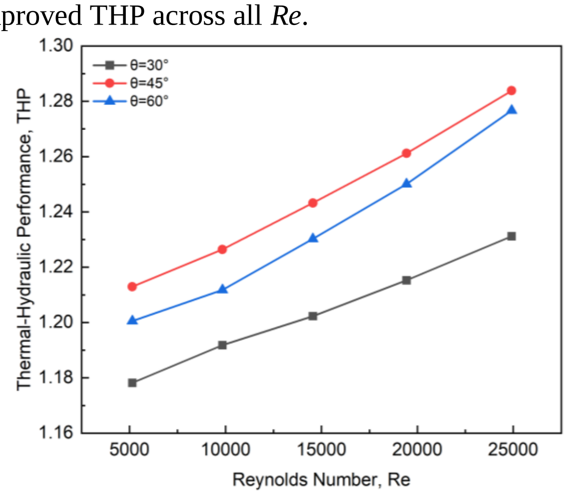

Fig. 4: The effect of attack angles, θ on THP against *Re*.

4. Conclusion

The effects of attack angle and punched hole diameter, as defined on KVGH, on thermal and hydrodynamic performance in the range of Re = 5000–25000 have been analysed through numerical work and research. The following are the conclusions that can be deduced from this investigation:

1) At each Reynolds number, *Re*, increasing the attack angle, θ leads to an increase in both the Nusselt number, *Nu* and the Darcy friction factor, *f*.
2) At all Reynolds numbers, *Re*, decreasing the punched hole diameter, d leads to higher thermal performance than hydrodynamic performance.
3) Attack angle and punched hole diameter, d, significantly influence the highest thermal-hydraulic performance (THP), with $\theta = 45°$ and $d = 2$mm yielding the highest THP value of 1.29.

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