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Performance Evaluation of Trapezoidal Ducts with Delta Wing Vortex Generators: An Experimental Investigation

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Abstract

This research investigates the performance enhancement of trapezoidal ducts through the integration of delta-wing Vortex Generators (VGs). Trapezoidal ducts, commonly used in various industrial applications, exhibit complex flow patterns that can hinder heat transfer and pressure drop characteristics. Delta-wing VGs, known for their ability to induce secondary flows and disrupt boundary layers, offer a promising solution to mitigate these issues. An experimental study was conducted to evaluate the impact of VG parameters, such as angle of attack, height, and spacing, on the flow and heat transfer performance

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of trapezoidal ducts. Detailed measurements of pressure distribution, velocity profiles, and temperature distributions were acquired using state-of-the-art instrumentation. The results demonstrate that the strategic placement of delta-wing VGs can significantly enhance heat transfer coefficients and reduce pressure drop. Optimal VG configurations were identified based on a comprehensive analysis of the experimental data. Moreover, the underlying mechanisms responsible for the performance improvements were elucidated through flow visualization and numerical simulations. The findings of this study provide valuable insights for the design and optimization of trapezoidal ducts in various engineering applications, including HVAC systems, heat exchangers, and gas turbine cooling systems. By effectively harnessing the potential of delta-wing VGs, it is possible to achieve significant energy savings and improved system performance.

Major Findings: *Vortex generators significantly enhance heat transfer, as indicated by increased Nusselt numbers compared to smooth ducts. The heat transfer improvement is more pronounced at higher Reynolds numbers, with the highest Nu/Nuo and Nu/NuD ratios observed at β = 30°. The Stanton number and thermal performance enhancement factor also confirm superior thermal performance with vortex generators.*

Keywords: Air Conditioning, Computer Programming, 2-D Design, Heating, HVACR, Optimization Algorithms, Ventilation

1.0 Introduction

Vortex Generators (VGs) have been widely used in various engineering applications to enhance fluid flow and heat transfer characteristics. Among the different types of VGs, delta-wing VGs have gained significant attention due to their simple geometry and effective performance. These VGs create vortices that interact with the boundary layer, leading to increased mixing, reduced boundary layer thickness, and improved heat transfer.

Trapezoidal ducts are commonly employed in various industrial applications, including ventilation systems, heat exchangers, and gas turbine cooling systems. However, the flow within trapezoidal ducts can be complex due to the non-uniform velocity and pressure distributions. To enhance the flow and heat transfer characteristics of trapezoidal ducts, the integration of delta-wing VGs has been proposed.

While numerous studies have investigated the performance of VGs in various geometries, including rectangular and circular ducts, limited research has been conducted on the application of delta-wing VGs in trapezoidal ducts. A comprehensive experimental investigation is necessary to assess the impact of VGs on the flow and heat transfer performance of trapezoidal ducts.

This research aims to experimentally investigate the performance of trapezoidal ducts equipped with delta-wing VGs. By systematically varying the VG parameters such as angle of attack, height, and spacing, the optimal configuration for enhanced flow and heat transfer will be determined. The findings of this study will contribute to the optimization of trapezoidal duct designs and provide valuable insights for various engineering applications.

2.0 Review of Literature

Saha reported a 55% increase in heat duty and a 47% reduction in pumping power by using axial corrugations and twisted-tape inserts in square ducts under turbulent flow, demonstrating significant thermal performance enhancement[1]. Rohsenow *et al.* in the *handbook of Heat and Mass Transfer,* provide essential equations and data regarding heat and mass transfer principles, particularly focusing on convection and conduction in various systems (sections 5.106, 11.34-11.40)[2]. Sohal explores the application of vortex generators to enhance the performance of air-cooled condensers in geothermal power plants, showing improvements in efficiency[3]. Wani *et al.* review the effects of vortex generators on flow characteristics and heat transfer in heat exchangers, emphasizing their role in improving performance across a range of applications[4]. Katti *et al.* investigated delta wing vortex generators (VGs) and found that increasing the pitch-to-height ratio reduced the friction factor, whereas higher height-to-duct diameter ratios and Reynolds numbers led to increased flow resistance[5]. Their findings highlight the importance of optimizing VG geometry to balance heat transfer improvement and pressure drop. In a similar vein, Pongjet Promvonge *et al.* examined the heat transfer and friction characteristics of a square duct outfitted with 30° angled finned tapes placed diagonally. They found that reducing the fin pitch spacing markedly

improved both the friction factor and heat transfer, suggesting that tighter fin arrangements boost surface interaction, enhancing heat dissipation while promoting turbulent mixing[6].

Qiuwang Wang *et al.* studied the use of Longitudinal Vortex Generators (LVGs) in a horizontal narrow rectangular channel, with water as the working fluid. Their experimental results indicated a significant improvement in heat transfer, ranging from 10% to 45%, when LVGs were placed on both sides of the duct, compared to a single side[7]. This finding emphasizes the importance of strategically placing vortex generators to maximize heat transfer by disrupting boundary layers more effectively. These studies collectively underscore the profound impact of flow enhancement techniques on thermal and fluid dynamic performance in various duct geometries.

J.S. Yang *et al.* conducted a numerical study to investigate the effects of common-flow-up pairs, produced by Vortex Ggenerators (VGs), in a rectangular channel. Their results revealed fluid flow and heat transfer characteristics that closely aligned with experimental data from other studies, highlighting the accuracy of the numerical simulations in predicting real-world flow behavior[8].

Chunhua Min *et al.* explored the fluid flow and heat transfer performance of modified Longitudinal Vortex Generators (LVGs) in a rectangular channel. They found that the modified wing pairs outperformed the traditional rectangular wing pairs, indicating that geometric modifications to the VG design can significantly enhance thermal performance[9].

J.M. Wu *et al.* examined the impact of various LVG parameters on heat transfer and pressure loss in a rectangular channel. They observed that as the LVG area increased, both the Nusselt number and flow loss penalty also rose[10]. However, increasing the length of the winglet pairs improved heat transfer for a fixed area, with delta winglet pairs proving to be more effective than rectangular ones, underscoring the importance of winglet design in optimizing heat exchange.

Hamdi E.A. Zangana studied the effect of vortex generators on friction in fully developed flow within a triangular duct. His findings showed a 43.5% improvement in the friction factor when the attack angle was varied from 30° to 50° for the triple pair case, demonstrating the influence of VG orientation on flow resistance[11].

Amit Garg *et al.*[12] numerically investigated forced convection in a triangular channel ribbed with longitudinal winglet vortex generators. Their results revealed that both the ribs and VGs significantly enhanced the Nusselt number and friction factor, indicating their combined potential to improve heat transfer in turbulent flow conditions[12]. Similarly, Azize Akcayoglu and Atole Santosh also contributed valuable experimental insights into the effectiveness of various VG configurations, further confirming the potential of vortex generators in improving heat transfer and flow dynamics in triangular ducts[13,14].

M. Darwish *et al.*[15] numerically studied natural convection heat transfer in partially divided trapezoidal cavities, investigating the effects of Rayleigh number, Prandtl number, baffle height, and baffle location on heat transfer. They found that baffles generally decreased heat transfer, with the rate increasing with baffle height[15].

LIU Haiyong experimentally explored the effects of various flow techniques, including impingement jets, swirl flow, cross flow, and effusion flow, within an enlarged model of a trapezoidal duct near a blades leading edge[16]. The findings revealed that smaller jets were effective in impinging the target wall, whereas larger jets induced a strong anticlockwise vortex. The literature review highlights that extensive research has been carried out to examine the impact of different flow enhancement methods on heat transfer and flow behavior in ducts. Much of the research focuses on mixed convection and internal flow within non-circular ducts such as square, rectangular, trapezoidal, polygonal, and triangular shapes. Although some studies have investigated the use of baffles and impingement jets in trapezoidal channels, very little research has explored the use of vortex generators in trapezoidal ducts.The studies by Kurhade *et al.* have significantly contributed to the understanding of heat transfer enhancement techniques, particularly through innovative inserts and materials in heat exchangers[17]. One notable work explored the use of wavy corrugated twisted tape inserts in double pipe heat exchangers, demonstrating how these inserts enhance turbulence, thus improving heat transfer rates[18]. Similarly, other studies by Kurhade *et al.* have focused on optimizing twisted tape inserts with circular holes and corrugated designs to further improve

forced convection heat transfer, which is crucial for the efficiency of thermal systems[19].

Additionally, Kurhade *et al.* have delved into the thermal performance of electronic components mounted on various substrate materials, showing how substrate properties influence the thermal management of electronic devices[20]. In another study, the performance of IC chips with and without Phase Change Materials (PCM) was compared, revealing significant improvements in thermal regulation when PCM was used, these studies underline the importance of effective cooling techniques for ensuring the reliability and longevity of electronic devices[21]. Further expanding on the thermal aspects, Waware *et al.* reviewed recent studies on nanofluids in heat exchangers, highlighting their potential for enhancing heat transfer properties[22]. This is an area of growing interest in thermal engineering, offering an avenue for improving the performance of heat exchangers in various industrial applications[23].

In terms of mechanical engineering, Yadav *et al.* presented a numerical and experimental investigation on the effect of the overlapping angle in arc welding processes. Their findings provide valuable insights for optimizing the welding process, contributing to the strength and deformation of welded curved plate[24,25]. Moreover, Kurhade *et al.* utilized fuzzy logic techniques to predict heat transfer enhancement with twisted tape inserts, showing the potential of Artificial Intelligence (AI) in optimizing heat exchanger designs[26,27].

Research by Kurhade *et al.* also contributed to understanding the role of material properties in the cooling of electronics[28]. For instance, the influence of substrate board thermal conductivity on the regulation of electronic component temperatures was numerically analyzed, highlighting the need for high-conductivity materials for effective thermal management[29]. Additionally, studies focused on the optimization of aerofoil designs through CFD simulations and wind tunnel experiments emphasized the importance of aerodynamic efficiency in various engineering applications including harsh environments[30-31]. Yadav *et al.* further extended the mechanical aspects of engineering by investigating the influence of plate thickness on the mechanical behavior of curved plates. This research provides valuable insights for the design and optimization of curved structures used in various engineering systems[32]. Similarly, Patil *et al.* explored the use of nanofluids in Minimum Quantity Lubrication (MQL) grinding, demonstrating their effectiveness in improving the cooling and efficiency of grinding processes[33,34].

Finally, Kurhade *et al.* also explored biodiesel and dimethyl carbonate blends in diesel engines, focusing on performance optimization and emission control. Their study offers promising solutions for reducing emissions while improving the performance of internal combustion engines[35,36]. Khot and Rao investigated the mechanical behavior of laser-welded butt joints in TRIP steel, focusing on the effect of laser incident angles on weld strength and deformation[37]. Their study provided valuable insights into optimizing welding parameters for enhanced joint performance. Expanding on this, Khot *et al.* analyzed various laser welding parameters and their impact on TRIP steel's mechanical properties, concluding that precise control over these parameters significantly improves weld strength[37]. Additionally, Khot and Rao examined the influence of quenching media on laser butt-welded TRIP steel joints, revealing that different quenching techniques affect the microstructure and mechanical characteristics of the welds[38].

Further, Khot *et al.* explored the effects of laser beam power and velocity on TRIP steel butt welds, emphasizing their critical role in determining weld quality, strength, and overall structural integrity[39]. In another study, Khot *et al.* applied experimental and machine learning approaches to predict the strength, deformation, and failure load of laser-welded TRIP steel, demonstrating the effectiveness of AI-driven techniques in welding optimization[40]. Lastly, Khot and Kadam performed a structural analysis of fillet weld joints in bimetallic curved plates using Finite Element Analysis (FEA), providing essential insights into stress distribution and weld joint stability[41]. Collectively, these studies contribute to advancing laser welding techniques for TRIP steel, offering significant benefits for structural, thermal and automotive applications. Kandharkar *et. al.*[42] has a detailed study of compliant mechanisms capable of transferring coplanar motion/force along with geometric amplification was undertaken and is presentated.

In this context, the heat transfer and flow characteristics of trapezoidal ducts were experimentally examined using delta wing Vortex Generators (VGs). Three distinct VG configurations were tested by varying the attack angle. Essential parameters such as inlet and outlet

temperatures and pressure drops were measured using appropriate instruments. The resulting Nusselt numbers and friction factors were then compared with empirical correlations from existing literature, offering valuable insights into the impact of vortex generators on duct flow dynamics.

3.0 Experimental Setup

The experimental setup, as illustrated in Figure 1, features a comprehensive arrangement for air flow analysis. Central to the system is a blower unit, which is connected to a test section at its delivery end. Positioned downstream of the blower, a flow control valve modulates the air flow through the test section. An orifice meter is installed further along the pipe to quantify the airflow rate. To regulate the air temperature, a heating element surrounds the section of pipe following the orifice. The test section itself is designed as a trapezoidal duct, where two pressure taps are strategically placed to capture pressure readings across the section. Differential pressure measurements are recorded by a U-tube manometer, both across the orifice and within the test section. To enhance flow control, delta wing Vortex Generators (VGs) are mounted on the duct's bottom surface. Surface temperatures are monitored with three thermocouples fixed to the duct's walls: One at the duct's inlet to measure incoming air temperature, another at the outlet to gauge the air temperature post-test, and one along the wall to track the thermal conditions within the duct itself. This setup allows for precise monitoring of airflow dynamics and thermal behaviours within the system.

Figure 1 presents the schematic diagram of the experimental apparatus. The duct system was crafted from a 1 mm thick galvanized iron sheet, incorporating a 1000 mm long inlet duct, an 800 mm test duct for assessing convection and fluid friction, and a 200 mm exit duct. The combined length of the inlet and test ducts ensured the establishment of fully developed turbulent flow. To ensure consistent heating, a nichrome wire electric heater was spirally wound around the duct's exterior, with power regulated at 150 watts using a variable-voltage transformer. The duct's 1 mm wall thickness promoted effective heat transfer by minimizing thermal resistance. Thermal insulation was provided by a 20 mm glass wool blanket and a 5 mm foam layer. Airflow was generated by a 0.56 Hp centrifugal blower, connected to the duct *via* a 60 mm diameter pipe, with flow rate adjusted by a control valve. Airflow measurements were taken using an orifice meter, while differential pressure across the test section was monitored with both a manometer and a digital pressure transmitter. Thermocouples were placed to measure the inlet and outlet air temperatures. The data gathered from the temperature and pressure readings enabled the calculation of forced convection and fluid friction characteristics within the system.

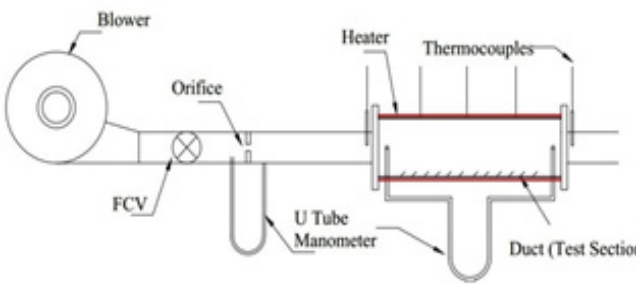


Figure 1. Experimental setup of a duct.

4.0 Numerical Analysis of Duct

Table 1. Specifications of the setup

Si. No.	Section of Apparatus	Dimension
1	Calibrated thermocouple (K type)	-270^{0}C to 1350^{0}C
2	Diameter of orifice (d)	30 mm
3	Armature	0 to 5A
4	Voltage range	0-270V
5	U-tube manometer	0-300 mm of WC
6	Inner diameter of pipe	60 mm
7	Test section length	900 mm
8	Capacity of blower	0.56 HP

The dimensions of various components are found out from the input parameters and various parameters of the standard components required are also specified as

Table 2. Input data for design

Si. No.	Parameters	Value
1	Mass flow rate (kg/sec)	0.02907
2	Inlet temperature (° C)	30
3	Outlet temperature (° C)	35
4	Specific heat (J/kg k) at 32.5° C	1007
5	Thermal conductivity (W/ mK)at 32.5° C	0.02625
6	Density (kg/m3) at 32.5° C	1.1450
7	Heat supplied (W)	150

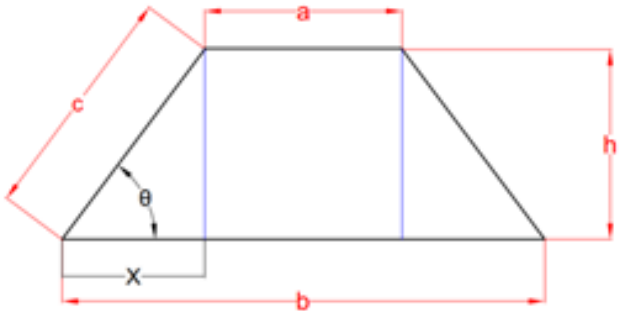


Figure 2. Cross-section of trapezoidal duct.

Table 2. Geometrical parameters of delta wing vortex generator

Parameter	Symbol	Value
Axial pitch	p	50 mm
Base	b	30 mm
Chord length	*l*	37.5 mm
Angle of attack	β	30°, 45°, 60°
Surface area	As_{vg}	562.5 mm^2
No of VG	n	16

shown in Table 1. The design methodology or procedure of the trapezoidal duct used in the experimentation. Also, the geometrical parameters of vortex generators are specified as per the Table 2. The geometrical parameters of delta wing vortex generators used in the present study are as per Table 3. These vortex generators are mounted in a single row on the bottom surface of the trapezoidal duct.

4.1 Duct Hydraulic Diameter Calculation

Consider that air is flowing through a duct and uniform heat supply of 150 W is given to the duct surface. Then the amount of heat transferred to air per unit time (heat transfer rate) is given by,

$Q = \dot{m}\, Cp\, \Delta T$

$Q = \dot{m}\, Cp\, (T_o - T_i)$

$150 = 0.02907 \times 1007 \times \Delta T$

$\Delta T = 5.12\ °C$

Convection Heat transfer from duct surface to air is given by,

$Q = h_c\, A_s\, (T_s - T_b)$ Where,

T_s & T_b = duct surface temp and bulk mean fluid temp of air respectively.

A_s = Duct Surface area or heat transfer surface area

h_c = convection heat transfer Coeff.

Here,

$$T_b = \frac{T_i + T_o}{2}$$

$$T_b = \frac{30 + 35}{2}$$

$T_b = 32.5\ °C$

To find Surface area of duct, we require h_c value *i.e.* convection heat transfer coefficient of air as well as surface temperature of duct surface. As the 'h_c' value of air lies in between 10 to 100 W/m^2k, here let us assume that, h_c = 30 W/m^2k. Here surface temp is also unknown. Thus, it is assumed that due to heat supplied surface temperature reaches to 60° C.

Thus, for $h_c = 30$ W/m^2k,

$T_s = 60°$ C and

$T_b = 32.5°$ C

Convection heat transfer is calculated by following relation,

$Q = h_c A_s (T_s - T_b)$

By putting all the known values,

$150 = 30 \times A_s \times (60-32.5)$

$A_s = 0.181818\ m^2$

Now if the test section of duct is of circular cross section having diameter *d* and length L, then considering L = 0.8 m,

Heat transfer surface area of circular duct is given by,

$A_s = \pi\ d\ L$

Putting all the values, Diameter of circular duct will be calculated as follows,

$A_s = \pi\ d\ L$

$0.181818 = \pi\ d \times 0.8$

$d = 72.34$ mm = 75 mm.

This value *i.e.* diameter of circular duct represents the hydraulic diameter of the circular duct. Thus,

$D_h = 75$ mm.

Now if we replace the circular duct with trapezoidal duct of same hydraulic diameter, the dimensions of Trapezoidal duct for (D_h= 75) mm are calculated as follows.

4.2 Duct design Calculations

Hydraulic diameter of duct is given by,

$D_h = 4A/P$ Where,

D_h = Hydraulic diameter

A = Area of cross section

P = Perimeter of cross section

Now, let us find the dimensions of trapezoidal duct.

Thus, from the flow and heat transfer characteristics for trapezoidal duct, aspect ratio (a^*) and angle between the base and slant height (θ) are selected as[26],

$a^* = 0.8$ and

$\theta = 60^o$

Dimensions for the trapezoidal duct as shown in figure can be calculated as follows. Aspect ratio is given by,

$a^* = a/h$

$0.8 = a/h$

$h = 1.25\ a$

Now as,

$\sin\theta = h/c$

$\sin 60 = 1.25\ a/c$

$0.866\ c = 1.25\ a$

$c = 1.25\ a/0.866$

$c = 1.4434\ a$

Also,

$\cos\theta = X/c$

$\cos 60 = X/c$

$0.5\ c = X$

$X = 0.5 \times 1.4434\ a$

$X = 0.7217\ a$

Area of trapezoid is given by,

$Area = 0.5\ (a + b) \times h$

$Area = 0.5\ \{a + (a + 2X)\} \times h$

$= 0.5\ (a + a + 1.4434\ a) \times 1.25\ a$

$= 1.7217\ a \times 1.25\ a$

$Area = 2.152125\ a^2$

Perimeter of trapezoid is given by,

$P = a + b + 2c$

$P = a + a + 1.4434\ a + 2.8868\ a$

$P = 6.3302\ a$

Hydraulic diameter of trapezoidal duct is given by,

$$D_h = \frac{4 \times Area}{P}$$

$$75 = \frac{4 \times 2.152125\ a^2}{6.3302\ a}$$

$474.765\ a = 8.6085\ a^2$

$8.6085\ a^2 - 474.765\ a = 0$

$a\ (8.6085\ a - 474.765) = 0$

$8.6085\ a = 474.765$

$a = 55.15$ mm = 55 mm.

Now,

$b = a + 2X$

$b = a + 1.4434\ a$

$b = 2.4434\ a$

$b = 2.4434 \times 55$

$b = 134.387$ = 135 mm.

And

$c = 1.4434\ a$

$c = 1.4434 \times 55$

$c = 79.387$ = 80 mm.

Height h of trapezoidal duct will be,

$h = 1.25\ a$

$h = 1.25 \times 55$

$h = 68.75$= 69 mm.

Thus, Dimensions of trapezoidal duct are,
Hydraulic diameter of duct,

Dh = 75mm

Cross sectional dimensions of duct

Top side, a = 55 mm

Bottom side, b = 135 mm.

Height, h = 69 mm

Angle, $\theta = 60^\circ$

Length of test section of duct (as assumed for circular duct)

L = 800mm

Length of entrance region = 1000 mm

Total length of duct = 2000 mm

Perimeter of duct

P = 350 mm

Heat transfer surface is of duct

As= 0.28 m^2

5.0 Results and Discussion

The study focused on investigating the heat transfer coefficients and friction factors within a trapezoidal duct operating under turbulent flow conditions. The research examined how different Reynolds numbers and Vortex Generator (VG) attack angles influence the flow dynamics and thermal performance of the duct. Three VG attack angles- 30°, 45°, and 60° were tested to evaluate their impact on the duct's flow and heat transfer characteristics. Among these configurations, the best thermal performance was achieved at an attack angle of 30°, which optimized the heat transfer process while minimizing frictional losses. The findings highlighted the significant role of the Reynolds number in affecting the flow behaviour and heat transfer rates. As the Reynolds number increased, both the turbulence intensity and heat transfer rates were enhanced, demonstrating the importance of operating conditions on performance. Additionally, the effect of the VG attack angle was evident, with the 30° angle providing the most effective disruption of the boundary layer, leading to a more uniform flow distribution and better heat dissipation. The study thus established that optimizing the attack angle of vortex generators is crucial for improving thermal efficiency and reducing flow resistance, providing valuable insights for the design of more efficient heat exchangers and fluid flow systems.

5.1 Surface Temperature

Figure 3 illustrates the variation in temperature along the surface of the smooth test section for a Reynolds number (Re) of 11,657. Experimental measurements of the surface temperatures of the test section revealed that the temperature variation along the flow direction was minimal. This consistent temperature profile suggests that the assumption of a constant wall temperature is reasonable for the given flow conditions. From the graph, the average surface temperature of the test section was determined by analyzing the temperature readings at various points along the surface for each specific Reynolds number. These average surface temperatures were calculated across a range of Reynolds numbers,

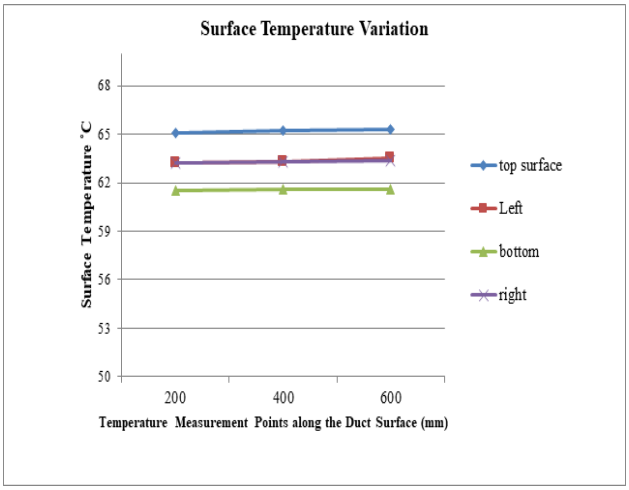


Figure 3. Variation of temperature on the surface of test section along flow direction.

spanning from 11,657 to 15,062, under steady-state flow conditions. The steady nature of the experiment ensured that the observed thermal characteristics were consistent and reliable, providing a solid foundation for further analysis of heat transfer and fluid flow behaviour within the duct system.

The experimental data were analyzed and presented graphically in Figure 4, showing the relationship between the Nusselt number (Nu) and Reynolds number (Re). To facilitate comparison, results obtained from a similar trapezoidal duct with smooth internal surfaces were also included on the graph. The data clearly indicate that the addition of Vortex Generators (VGs) leads to an increase in the friction factor. However, as the Reynolds number increases, the friction factor decreases. The highest friction factor of 0.0523 occurred at a Reynolds number of 11,657 for the 60° VG configuration, while the lowest friction factor, 0.0349, was observed at a Reynolds number of 15,062 for the 30° VG configuration. The addition of vortex generators resulted in a percentage increase in the friction factor compared to the smooth duct, ranging from 14% to 21% for a 30° VG, 19% to 36% for a 45° VG, and 31% to 49% for a 60° VG, across the Reynolds number range considered.

Figure 5 illustrates the variation of the friction factor ratio with Reynolds number. The ratio was calculated by comparing the friction factor for the duct with VGs to the friction factor of the smooth duct at the same Reynolds number. From the graph, it is evident that the friction

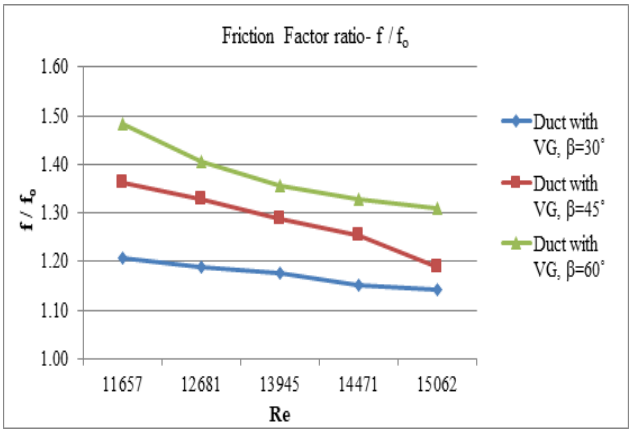


Figure 5. Friction factor ratio vs Reynolds number.

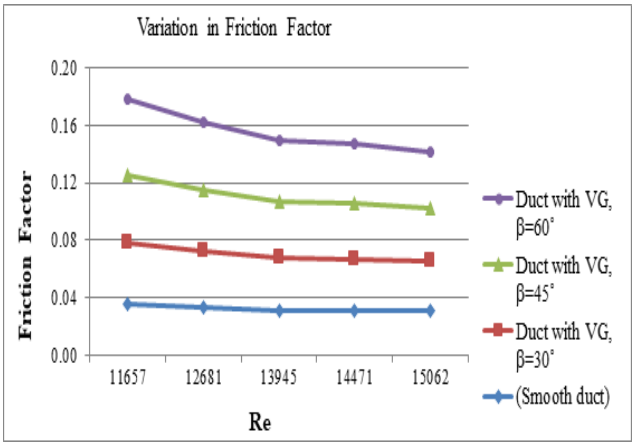


Figure 4. Effect of Reynold number on friction factor.

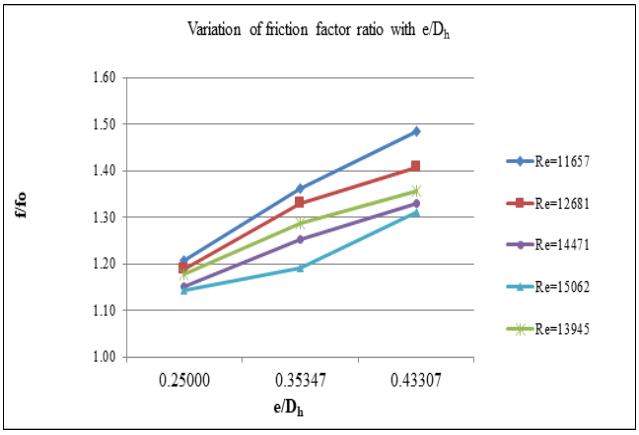


Figure 6. Friction factor ratio *vs* (e/D$_h$) ratio.

factor ratio decreases with an increasing Reynolds number. At the lowest Reynolds number (Re = 11,657), the friction factor for the 30° VG duct was 1.207 times greater than that of the smooth duct.

For the 45° and 60° VG configurations, the ratios were 1.362 and 1.483, respectively. At the highest Reynolds number (Re = 15,062), the friction factors were 1.143, 1.19, and 1.31 times greater than the smooth duct for the 30°, 45°, and 60° VG configurations, respectively.

Interestingly, unlike the Nusselt number, the friction factors were smaller at higher Reynolds numbers. This trend is attributed to the inverse relationship between the Reynolds number and the friction factor. As the Reynolds number increases, the flow velocity also increases, which reduces the friction factor due to the higher flow energy, despite resulting in higher pressure drops and greater power requirements to maintain fluid flow. This relationship underscores the complexity of optimizing duct designs, where enhancing heat transfer through vortex generators can simultaneously increase the friction factor, but the effect diminishes with higher Reynolds numbers.

Figure 6 illustrates the variation in the friction factor ratio with the ratio of the height of the Vortex Generator (VG) from the duct surface to the hydraulic diameter (e/Dh). In this study, the hydraulic diameter of the duct was maintained constant, while the height (e) was determined using the chord length and the attack angle of the VG. For a specific Reynolds number, the graph shows how the friction factor ratio changes with different values of e/Dh. From the graph, it is evident that the friction factor ratio increases as the value of e/Dh rises. This trend can be attributed to the fact that the height of the vortex generator influences the strength of the vortices created in the flow. The angle of attack of the vortex generators is directly proportional to their height, meaning that an increase in the height (e) results in a larger attack angle. As the attack angle increases, the strength and core size of the generated vortex intensify, leading to greater flow disturbances. Furthermore, the increase in the height of the VG (e/Dh) leads to a larger projection area of the delta wings that is normal to the incoming flow, creating more obstruction or blockage to the flow. These disturbances, caused by stronger longitudinal vortices, result in an increase in the pressure drop. Consequently, the friction factor ratio increases with a higher e/Dh value, as the intensity of the vortex generation and its disruptive effects on the flow become more pronounced. Thus, while vortex generators improve heat transfer, their size and attack angle must be carefully optimized to balance the benefits of heat dissipation with the associated increase in flow resistance.

5.0 Conclusion

Vortex generators at optimal angles of attack likely resulted in significant improvements in heat transfer coefficients compared to the baseline case without vortex generators. The following conclusions are drowning from the research

1. For all the cases, the Nusselt number increase with the increase in Reynolds number. For the smooth duct, this is due to more mass flow rate of air available to carry the generated heat. But when the results of the Nusselt number for smooth duct and duct with VG were compared for the same mass flow rate, heat transfer rate was observed to be increasing for the duct with VG. This is a clear indication of influence of vortices produced by delta wing on the heat transfer rate.
2. The ratio of Nusselt for duct with VG to that of smooth duct increases with the increasing Reynolds number. For $\beta = 300$, higher values of Nu/Nuo were reported *i.e.* 1.668 and 1.296 over the range of Re.
3. When the comparison of experimental and theoretical results was made, the ratio Nu/NuD was observed to be higher for $\beta = 300$. It was 1.19 and 1.69 over the range of Reynold number considered.
4. The Stanton number (St) reported during the experimentation was 1384 and 796 for $\beta = 300$ for the range of Reynold number considered.
5. Thermal-performance Enhancement Factor (TEF) was reported to be 1.217 and 1.595 for $\beta = 300$.

6.0 Author Contribution

Gokul Navnath Wakchaure, Yatin Madhukar Bhamare: Experimental Setup preparation and test conduct. Tushar A. Jadhav, Ajaykumar Jagtap: Elaboration of

results and discussion session. Pabbathi Vijayarao, Rahul Gaji: Preparation of Literature review and providing meaningful insights with major findings. Avinash Shivajirao ChavanPatil, Sunil D. Kamble: Justification of comments after reviewing the article. Sagar Vijay Jagtap: Preparation of graphical abstract. Rahul Shivaji Yadav, Anant Sidhappa Kurhade: Reviewer suggestion, communication with editor, reference section, and preparation of video

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