Numerical Simulation of Low Pressure Evaporator Modified with Vortex Generator for Improving the Heat Transfer Characteristics

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Abstract. Heat Recovery Steam Generator (HRSG) is a crucial component in the combined cycle power plant, which utilises gas turbine exhaust gases to heat water into further hot steam. Research is needed to improve the heat transfer process in the LP Evaporator. One way to increase the heat transfer is by adding a Vortex Generator (VG) to the LP evaporator. The Vortex Generator itself is a vortex generator that aims to make the fluid flow from the gas turbine not only hit the tube banks in the HRSG but also between the tubes installed a Vortex Generator, which functions to make the fluid flow that was previously laminar into turbulent so that the heat transfer that occurs in LP Evaporator just got better. The analysis consists to velocity contour, temperature contour, local Nu, heat transfer (q), and pressure drop. To determine fluid flow using 2D simulation with Computational Fluid Dynamics (CFD). From the geometry type. Variations made are geometric shapes and the VG arrangement, namely rectangular common flow down, delta winglet common flow down, delta winglet common flow up, and rectangular common flow up. The heat transfer rate value is 2271.34 W, 2333.27 W, 3340.334 W, 3090.747 W. The highest heat transfer rate value occurs on the delta winglet with the common flow up arrangement, and the lowest heat transfer rate value occurs on rectangular with the common flow down arrangement.

1. Introduction
A Steam Power Plant is a power plant that uses coal as its fuel. The coal will then carry out the combustion process to produce steam used to drive a steam turbine to produce electricity. The Ministry of Home Affairs and Mineral Resources states that the electrification ratio in Indonesia in 2020 is 98.89. For now, the primary source of support for the national electricity needs is still the steam power plant [1]. Therefore, it is necessary to increase electricity production in Indonesia, but currently efforts to increase output leave a not good impact on the community around the steam power plant area. Based on data from the Ministry of Energy and Mineral Resources in 2017, it was founded that the steam power plant has 30,208.32 MW of 60,789.98 MW, which means that the steam power plant participates in almost 50% of electricity needs in Indonesia. This impact is caused by the power plant that uses low-quality and cheap coal fuel to increase electricity production.

In addition to a steam power plant, there is also a contributor to the second national electricity demand, namely the combined cycle power plant. The combined cycle power plant is a combination of
a gas power plant and a steam power plant where the exhaust gas from the gas turbine will produce pressurized steam. This gas temperature is still high so that it can be used to convert water in the Heat Recovery Steam Generator (HRSG) tube into dry steam to drive steam turbine blades. The advantage of HRSG compared to boilers is the increase in efficiency because HRSG utilizes exhaust gas from gas tubing as a heat source without requiring fuel. HRSG has several components, namely superheater, evaporator, and economizer, composed of tubes with a specific structure and number that affect HRSG performance [2]. One way to increase heat transfer in the LP Evaporator is by adding a Vortex Generator (VG) so that the exhaust gases from the gas turbine not only hit the tube on the HRSG but also hit the VG. According to the theoretical principle which reads that the more turbulent the flow in a system, the better the displacement.

The efficiency decrease in HRSG that often occurs can be caused by several factors, such as the appearance of deposits (fouling) on HRSG pipes to cause narrowing of the area in the tube [3]. The narrowed area can cause plugging in the superheater tube, and the mass of fluid flow will decrease due to the smaller diameter. If this condition lasts for a long time, the amount of attached scale will increase, and it will inhibit the transfer of heat from the heating tube to the feedwater to be converted into steam so that the HRSG efficiency will decrease.

In addition, corrosion is caused by sulphur contained in High-Speed Diesel (HSD) oil from gas turbines. Corrosion can cause thinning of the tube in the HRSG if left continuously, allowing leakage of the pipes. Leaks that occur can be in the form of the formation of holes and rupture of the tube. The company’s current cleaning method, and the lower efficiency of HRSG is getting bigger than closer to the cleaning period.

Zhimin Han et al. [4] conducted research, namely the addition of a Vortex Generator to (VG) the Shell and Tube Heat Exchanger can reduce fouling resistance by 19% for rectangular VG. In addition, the fouling resistance decreases with the addition of the height and length of the VG. However, what needs to be considered is the pressure drop, the longer, and the higher VG, increasing pressure drop. Therefore, selecting VG shape and VG placement is very important for a good combination to increase HRSG efficiency.

Research on the addition of a Vortex Generator to the Heat Exchanger was carried out by Zhiqiang Sun et al. [5]. With the title "Investigations of the turbulent thermal-hydraulic performance in circular heat exchanger tubes with multiple rectangular winglet vortex generators". The results of the Turbulent Kinetic Energy (TKE) in the tube with Vortex Generator increase with high VG, which indicates the vortex-induced by VG which higher will result in better fluid mixing. So that the average temperature is high and the temperature distribution is uniform. Then examine the effect of the angle and length of the obstacle on tube banks arranged staggered on the Num and pressure drop characteristics. The results show that the greater angle and size of the VG, the higher the Num and pressure drop.

In addition to Vortex Generator in tube banks, research in other fields in power generation has been carried out. It is crucial to develop the electrification of an area. Research that discusses the effect of fuel changes on the performance of power plants [6,7]. Then there is also research that discusses the investigation of water cooling condensers and their impact on power plants [8].

Based on the description above, the importance of the impact of HRSG on a combined cycle power plant. The varied forms are rectangular and delta winglet Vortex Generator with common flow up and common flow down arrangement. It is hoped that the best and suitable arrangement will be obtained to increase the efficiency of the combined cycle power plant.

2. Numerical Method

This research uses Computational Fluid Dynamic (CFD) software to determine the effect of vortex generators with geometry and arrangement variations with 2D modelling. CFD is a system analysis methodology involving fluid flow, heat transfer, and related phenomena using computer-based simulations. The modelling steps are divided into three stages, namely pre-processing, processing, and post-processing.
2.1 Geometry
At this stage it is divided into two making geometry and meshing. The geometric design was made using spaceclaim 19.1 software by simplifying it into 4 tubes and 3 rows with 2D simulations.

![Figure 1. Geometry of tube banks.](image)

| Geometry | Dimensions |
|----------|------------|
| Diameter tube (D)       | 12.7 mm    |
| Longitudinal pitch (Sₖ) | 27.559 mm  |
| Transverse pitch (Sₜ)   | 31.496 mm  |
| Longitudinal tube pitch (Sₖ/D) | 2.17 mm |
| Transverse tube pitch (Sₜ/D) | 2.48 mm |
| Radial distance (R/D)   | 0.74 mm    |
| Circumferential angle obstacle (α) | 30° |
| Length of VGs           | 4.953 mm   |
| Width of VGs            |            |
| Upstream extended region| 1.0033 mm  |
| Downstream extended region| 8 D       |
| Longitudinal tube pitch (Sₖ/D) | 20 D     |

In this research using variations on geometry and arrangement. Variation explanations are found in Table 2.

| Variations | Types       | Arrangements          |
|------------|-------------|-----------------------|
| Baseline   | -           | -                     |
| 1          | Rectangular | Common Flow Down      |
| 2          | Delta Winglet | Common Flow Down     |
| 3          | Delta Winglet | Common Flow Up       |
| 4          | Rectangular | Common Flow Up       |

2.2 Meshing
Meshing is a continuous process of discretizing fluid domains into discrete computational domains so that equations (in this case, fluid flow) can be solved and produce solutions. In simple terms, the
discretization process (the mathematical representation of meshing or gridding). This study used a tetrahedral mesh with a skewness quality 0.774. The following type of mesh showed in Figure 2.

![Meshing of tube banks](image)

**Figure 2.** Meshing of tube banks.

After doing meshing, grid independent aims to ensure the accuracy and validity of data from numerical results. There are five variations of a number of cell 54969, 73650, 94580, 114580, 136659, 145370, 154920, and 1310685. Therefore, grid independence this time uses the baseline case or when tube banks are without obstacles with parameters such as D = 12.7 mm S_L = 2.17D, S_T = 2.48 D and ReD: 4000.

![Grid independent graph](image)

**Figure 3.** Grid independent graph.

### 2.3 Processing

Processing is the main stage of CFD simulations. At this stage, the solution is calculated based on the conditions applied in the pre-processing step. At this stage, insert the value from the boundary layer. The fluid used is incompressible air with constant properties. The assumptions used are 2D turbulence flow, uniform, steady, no viscous dissipation, and radiation effects are ignored.
Table 3. Boundary conditions.

| Surface   | Boundary Condition          |
|-----------|----------------------------|
| Inlet     | Velocity inlet             |
|           | Vin: 5 m/s                 |
|           | Tin: 300 K                 |
| Outlet    | Outflow                    |
| Tube      | Stationery wall            |
|           | Tw: 350 K                  |
|           | Material type: Copper      |
| VGs       | Stationery wall            |

Table 4. Properties of fluid.

| Materials | Settings                                    |
|-----------|---------------------------------------------|
| Air       | Density: 1.1614 kg m\(^{-3}\)              |
|           | Specific heat (cp): 1.007 kJ kg\(^{-1}\) K\(^{-1}\) |
|           | Viscosity: 1.846x10\(^{-5}\) kg m\(^{-1}\) s\(^{-1}\) |
|           | Thermal conductivity: 0.0263 W m\(^{-1}\) K\(^{-1}\) |
| Copper    | Density: 8.978 kg m\(^{-3}\)              |
|           | Specific heat (cp): 381 kJ kg\(^{-1}\) K\(^{-1}\) |
|           | Thermal conductivity: 387.6 W m\(^{-1}\) K\(^{-1}\) |

The simulation set up for this paper uses the finite volume method. The algorithm is SIMPLEC. The Standard k-epsilon is used as a viscous turbulent model. The governing equations such as continuity equation, momentum equation, energy equation are discretized by the second-order upwind numerical scheme. Pressure discretized by the standard. The solutions are converged when the continuity residual value is 10\(^{-4}\) for all variables and then 10\(^{-6}\) for the energy equation.

2.4 Heat Transfer Equations

The Reynolds number is used to identify different types of flow, such as laminar and turbulent:

\[
\text{Re}_D = \frac{\rho v_{max} D}{\mu} 
\]

(1)

After that, calculate the value of the convection heat transfer coefficient with the equation:

\[
h = N\text{u}_{D} \frac{k_f}{D} \]

(2)

So, the value of heat transfer rate per unit length on the tube can be calculated, with [10] :

\[
q = (h\pi DL) \]

(3)
3. Results and Discussion

3.1 Validation
The validation is used to ensure that the viscous turbulence model in this study is valid. This study uses The Standard $k$-epsilon as a viscous turbulent model. For verification can be seen in Figure 4, this research compares the value of Nusselt numbers from Romandhoni’s numerical study [9] at tube row 3 and numerical studies based on my simulations.

![Figure 4](image.png)

Figure 4. The validation of Nu in Tube Row 3.

3.2 The Effect of Vortex Generator on Velocity Contour and Temperature Contour
Figure 5 showed about velocity contour an in the common flow down arrangement, and the Vmax value occurs the highest in the VG delta winglet form, which is 12 m/s. Meanwhile, the highest Vmax appears in the VG delta winglet form in the common flow up arrangement, which is 24 m/s. For comparison of velocity contour results, it can be seen that V max occurs in tube row 2 in each variation and baseline. This is following the Zukauskas correlation equation.

Where for the best arrangement is common flow up because in the common flow up arrangement, the VG placement is on the side of this tube, causing a high flow blockage effect so that it can trigger a high-pressure drop as well. Meanwhile, in the common flow down arrangement, the VG is placed around the rear tube, which causes a blockage effect in the flow that is not too high. If observed more deeply in the baseline case, the fluid flow velocity will approach zero at the front of the tube (stagnation point). Then the speed will increase around the rear tube and will decrease until the separation point. Then there is backflow at the back of the tube (downstream).

While in variations 1 and 2, namely the arrangement of the common flow down, different things occur. At the stagnation point, the fluid flow velocity will approach zero, and then the speed will increase around the rear tube and in the gap between the tube and the VG. Furthermore, in the downstream, backflow occurs but not as much as in the baseline case. Besides that backflow also appears at the back of the VG. It can be concluded that adding rectangular VG can affect the flow characteristics in the downstream section and then divert it at the back of the VG.

Then in variations 3 and 4, namely the arrangement of the common flow up, at the stagnation point, the fluid flow velocity approaches zero. Then the fluid velocity will increase in the rear tube and the gap between the tube and VG. The placement of VG at the top and bottom of the tube increased speed is divided into two on the sides of the VG. Then there is also a very wide backflow at the rear of the VG. This is because the placement of the VG itself causes a blockage effect on the fluid flow.

This has been conveyed in previous studies where the occurrence of backflow indicates a low heat transfer rate that occurs [8]. So it can be concluded that adding VG type common flow up and common flow down can delay the occurrence of backflow in the downstream tube. The backflow is diverted to the rear of the VG so that the heat transfer process that occurs in the tube is increasing.
Figure 6 showed us about temperature contour in tube row 3. In the inlet fluid, the air is set at a temperature of 300 K. On the side of the tube wall, the temperature is set at 350 K. The author takes the contour of the temperature data on the third-row tube caused by the fluid hitting the row 3 tube through the tube row 1 and 2 so that the results of the addition VG can be seen more clearly in tube row 3. The results of the temperature contour in the baseline case show that the maximum temperature only occurs around the tube wall. This happens because there is a thermal boundary layer on the tube surface so that the heat transfer process from the fluid to the air is less than optimal.

Then the effect of the addition of VG on the downstream side of the rear tube can cause an increase in the momentum of the fluid in the back tube and tube rows 2 and 3. This increase in momentum causes the mixing of the fluid between the fresh flow in the upstream. In variations b and c, the addition of VG with a common flow down arrangement can increase fluid mixing downstream and disrupt the formation of a thermal boundary layer on the tube surface so that the heat transfer that occurs in the tube increases.

Furthermore, in variations d and e, the addition of VG with a common flow-up arrangement causes a blockage effect on the fluid flow. This causes backflow at the back of the VG, which was initially on the downstream side of the tube. So it can delay the occurrence of the thermal boundary layer on the tube surface earlier.

Figure 5. Velocity contour.
3.3 The Effect of Vortex Generator on Local Nu in Tube Row 2

Based on Figure 7, a visualization of the local distribution of Nu in tube row 2 increases with the addition of VG compared to the baseline case. At baseline, there is a decrease in the local value of Nu when the flow crosses the tube at the flow position $\theta = 0^\circ$ until the angle reaches $110^\circ$ the local value of Nu reaches its lowest point. Then, the local value of Nu fluctuates when the flow crosses the tube position $110^\circ \leq \theta \leq 180^\circ$. The increase is caused by the formation of vortexes in the area.

When viewed from the analysis of the velocity contour at that point, the local tube velocity also increased. In this case, the local value of Nu will increase as the flow velocity increases at that point. Then in variations b and c, when added to the VG common flow down arrangement, the local distribution of Nu is almost the same as the baseline case. This can be caused by the placement of VG, which is in the downstream tube so that the fluid flow in tube row 2 is not too different from the baseline case. However, in (delta winglet vortex generator), there is a significant local increase in Nu at the point $\theta = 125^\circ$ to $140^\circ$. This indicates the formation of vortexes in the area. This phenomenon was also observed by Romandhoni et al. [9], who defined that the occurrence of local fluctuations in Nu indicated a separate reattachment and shear layer from the tube. The shear layer is divided into two streams, one moves towards the downstream tube following the contour of the obstacle, and the other is deflected.
3.4 The Effect of Vortex Generator on Local Nu in Tube Row 3

Based on Figure 8, in tube row 3 shows a local distribution pattern of Nu which is similar to tube row 2. Compared to tube row 2, there is a local decrease in Nu due to the influence of fluid flow entering the gap between VG and the tube, which then partially oscillates, which is indicated by the recirculation zone. In a study conducted by Romandoni et al. [9] it was stated that the recirculation zone area means the low heat transfer that occurs in that position. It can be proven that there is a local decrease in Nu at places $\pm 90^\circ$ to $\pm 180^\circ$ the formation of a flow vortex resulting in a reduction of heat transfer.

In addition, an increase in flow velocity, which also results in increases in the value of the local distribution of Nu, also occurs because there is a blockage effect caused by the VG that has been described previously. In the VG common flow down arrangement, the local distribution of Nu is lower than the common flow up arrangement. This occurs because the blockage effect phenomenon is weaker than in the common flow-down arrangement.

3.5 The Effect of Vortex Generator on Heat Transfer ($q$)

Based on Figure 9, the comparison graph of the heat transfer value in the baseline case with the addition of a vortex generator. The effect of adding VG has an impact on increasing heat transfer ($q$) on tube banks. The highest $q$ value occurs in the delta winglet with a common flow up arrangement of $q = 3340.334$ W, and the lowest occurs in rectangular with a common flow down arrangement of $q = 2271.034$ W.
3.6 The Effect of Vortex Generator on Pressure Drop ($\Delta P$)

Although the addition of Vortex Generator resulted in a very significant increase in local $\text{Num}$, it should be noted that this phenomenon is also directly proportional to the increase in pressure drop. This is due to the drag force generated by VG. Table 5 showed the pressure drop in each variation. In the common flow down arrangement, the increase in pressure drop that occurs is not as significant as what happened in the common flow up arrangement. The highest value of pressure drop is variations 3 ($\Delta P = 382.449 \text{ Pa}$) and the lowest value of pressure drop is variation 1 ($\Delta P = 62.913 \text{ Pa}$).

| Variations | Types         | Arrangements          | Pin (Pa) | Pout (Pa) | $\Delta P$ (Pa) |
|------------|---------------|-----------------------|----------|-----------|-----------------|
| Baseline   | -             | -                     | 14.517   | -14.101   | 28.619          |
| 1          | Rectangular   | Common Flow Down      | 14.517   | -48.396   | 62.913          |
| 2          | Delta Winglet | Common Flow Down      | 18.079   | -60.698   | 78.778          |
| 3          | Delta Winglet | Common Flow Up        | 20.155   | -362.294  | 382.449         |
| 4          | Rectangular   | Common Flow Up        | 20.284   | -256.757  | 277.041         |

3.7 Effectiveness

The simulation results obtained data on pressure drop ($\Delta P$), heat transfer ($q$), and effectiveness, as shown in Table 6. Effectiveness is used to determine the most optimum obstacle with the most considerable value or can be expressed in the Equation 4.

$$\frac{q}{\Delta P} = \frac{q_2 - q_1}{\Delta P_2 - \Delta P_1}$$

| Variations | $\Delta P$ (Pa) | $Q$ (Watt) | Effectiveness |
|------------|-----------------|------------|---------------|
| Baseline   | 28.619          | 2147.371   | -             |
| 1          | 62.913          | 2271.034   | 0.0480        |
| 2          | 78.778          | 2333.27    | 0.1086        |
| 3          | 382.449         | 3340.34    | 0.1119        |
| 4          | 277.041         | 3090.747   | 0.2711        |
In Table 4, the result is V4 (rectangular vortex generator with a common flow up arrangement) as a highest effectiveness value, which is 0.2711.

4. Conclusions

Based on the study that has been done, it was concluded that:

1. Heat transfer that occurs in tube banks with added vortex generators is better than the baseline model. The highest $q$ value appears in the delta winglet with a common flow-up arrangement, $q=3340,334\text{W}$, and the lowest is in a rectangular vortex generator with a common flow-down arrangement $q=2271,034\text{W}$.

2. The addition of a vortex generator also results in a higher pressure drop value. Based on the simulation results, the highest pressure drop value occurs in the delta winglet vortex generator with a common flow-up arrangement $(\Delta P=382,449\text{ Pa})$ and the smallest in a rectangular vortex generator with a common flow down arrangement $(\Delta P=62,913\text{ Pa})$.

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