Numerical Study the Effect of Gap Ratio on Flow Characteristics and Heat Transfer in Staggered Tube Banks

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Abstract. Condenser is a type of heat exchanger that serves as condensation for turbine output steam. In general, a steam power plant uses a surface condenser. This type of condenser is a type of shell and tube. Condensers have a phenomenon of convection heat transfer. The change in distance between condenser tubes is one way to increase the rate of heat transfer. To produce maximum heat transfer, it can be determined by the variety of distances between tubes. The research was conducted by analyzing the flow characteristic and heat transfer around condenser tube banks with gap ratio variation (s/d), which compares transverse distance (S_T) and tube diameter (d) with variations of 3.2, 2.7, 2, and 1.7. 2-dimensional simulation with Computational Fluid Dynamics (CFD) is a numerical method and algorithm for solving and analyzing problems that occur in fluid flows. Based on the results obtained, the smaller the Gap Ratio, the lower the outlet temperature produced and the maximum heat transfer, but the pressure drop value obtained the bigger. Also, the smaller Gap ratio, the bigger v_max produced. The lowest outlet temperature value at the variation of 1.7 is 310.66 K, and the coefficient of heat transfer is 103.34 W/m²K. Pressure drop produced at variation 1.7 is 515.99 Pa. Variation 2 is the best gap ratio variation, seen from the heat transfer result and the pressure drop value is not too large. The coefficient heat transfer and pressure drop in variation 2 are 76.95 W/m²K and 119.17 Pa.

1. Introduction
In the steam power plant, an energy conservation process is carried out based on the working principle of the Rankine cycle, which consists of four main components, namely a boiler, pump, condenser, and turbine. The condenser is a component that serves to condense the steam from the turbine. In the condenser, the steam from the turbine comes in contact with the tube, which is flowed by cooling water so that the steam turns into a liquid. In general, steam power plant uses a surface condenser. This type of condenser is a shell and tube type.

The flow and heat transfer characteristics of the condenser have the phenomenon of convection heat transfer. In this phenomenon, the distance between the tubes can affect the heat transfer that occurs. To provide maximum heat transfer, it can be determined by varying the distance between the tubes. From these variations, it will be determined the maximum in the heat transfer process.

Prayudi [1], working from the condenser influences the performance Rankine cycle—condenser otherwise good performance when the heat transfer process that occurs in the condenser is progressing well. The Heat transfer process is influenced by several things such as the cleanliness tube, the amount of refrigerant flowing water, cooling water inlet temperature.
Rizki [2], another effort to maximize the heat transfer process on continuous plate fins can also be formed by adding obstacles to the surface. In this research, the varied angle position of rectangular obstacles at slopes of 120°, 135°, and 150° based on the central point of the tube measured from stagnation point, with a fixed obstacle length of 2.5 mm and a width of 0.5 mm on stationary tube banks. The results of this simulation obtained visualization of contours of velocity, temperature, and visualization of formed flow patterns and hypothetical proof that obstacles will increase heat transfer.

Karnav N Shah [3], researched that focused on simulating different tube angle settings of 30°, 45°, and 60° on the influence of heat transfer. From the analysis obtained, CFDs are the best method to predict fluid flow, heat transfer & mass phenomena related to numerically solving mathematical equations that govern mass conservation, momentum, energy, species, etc. The result is for pressure drop between simulation and calculation result for 45° angle setting (ST=const.) Compared to the 60° angle setting (ST=const.), but the pressure drop obtained at 60° is less than 45°. Santosa [4], the overall heat transfer coefficient of two CO2 gas coolers was investigated through experiment and CFD. A horizontal row of tubes of the gas cooler can increase the overall heat transfer coefficient by 8% compared with the fin without the slit. Ruonan [5], configuration of finned tube bundles and complex aerodynamics of axial flow fan result in the increased pressure loss of cooling air and unfavorable thermo-flow performances of air-cooled condenser cell. Xiaojing [6], The mean within-tube condensation heat transfer coefficient in increases greatly when the latter two increase, while the increase in the difference between steam and tube wall temperature hinders the mean within-tube condensation heat transfer coefficient.

Power plants play a crucial role in the need for electrical energy. Research’s and innovations in the field of power plants significantly impact the advancement of electrical technology. Trisnayanti et al. [7] and Satrio et al. [8], researched the fuel side, where the research aimed to determine the effect of fuel replacement on performance and fuel consumption in a steam power plant. Kurniawati et al. [9], researched one of the main components in the power plant, the condenser. This research aims to determine the performance of the condenser and the efficiency of the power plant cycle, which is influenced by the temperature and flow rate of the cooling water.

This research will analyze the characteristics of the flow and heat transfer fluid with the effect of changes in the distance between tubes, which is stated in the s/d parameter (Gap Ratio), which is the ratio between the distance between tubes and the tube diameter (d) using a variation of the transverse distance \( S_T \) with a variation of 1.7, 2, 2.7, and 3.2. Computational Fluid Dynamics (CFD) is a numerical method and algorithm for solving and analyzing problems in fluid flow. In this research, CFD is used to obtain flow characteristics and fluid heat transfer in the form of velocity, streamline, and vector profiles around the condenser tube. It is expected that this research will obtain a gap ratio that produces maximum heat transfer. Halim [10], increasing the s/d gap ratio causes the airflow velocity to grow, as seen from getting bigger air velocity vector velocity and area.

2. Numerical Method

2.1 Pre-processing

Pre-processing is the initial process of CFD simulation. This numerical study was conducted by creating a test model adjusted to the dimensions and geometry in the actual state.

2.1.1 Geometry and Boundary condition

Figure 1 is the 2-D geometry design. The research did not simulate condenser as a whole. The geometry of the condenser drawn is only part of the tube. Condenser design data is a reference in creating geometry, as in Table 1.
In this research using variations on geometry, namely gap ratio. Variation explanations are found in Table 2.

| Model | $S_T$     | Gap Ratio |
|-------|-----------|-----------|
| A     | 81.4 mm   | 3.2       |
| B     | 69.4 mm   | 2.7       |
| C     | 51.4 mm   | 2         |
| D     | 45.4      | 1.7       |

Variable information to be simulated is entered as a value parameter for each boundary condition in Table 3. Explanation of the boundary condition model in Figure 1.
Table 3. Boundary conditions.

| Boundary Conditions | Information |
|---------------------|-------------|
| Inlet               | Type: Velocity Inlet  
                   | Velocity: 7.07 m/s  
                   | Temperature: 318.05 K |
| Outlet              | Type: Outflow |
| Tube                | Type: Stationary Wall  
                   | Thermal Condition:  
                   | Temperature  
                   | Free Steam Temperature: 306.35 K |
| Symmetry            | Type: Symmetry |

2.1.2 Mesh

Figure 2 is meshing done based on geometry. Mesh used is a type of triangle because it tends to be more structured when used on the geometry of cylinder tubes.

2.2 Processing

The next stage in CFD is processing, using CFD software. The modelling stages carried out in this process include setting the solver model, viscous model, materials, operating conditions, control and monitoring conditions.

2.2.1 Solver Model

2-dimensional (2D) solution is used to solve the problem. The solver used is pressure-based, which is a pressure-based solver with steady time conditioning. The energy equation is activated to support the solution for heat transfer. While for the turbulence modeling of selected k-RNG (Renormalization Group). The enhanced wall treatment menu is activated by selecting the pressure
gradient effect and thermal effect options to support the accuracy of the iteration results in the area near the wall.

2.2.2 Material

In this research simulation, there are two kinds of materials used. The working fluid that flows is modeled as water vapor and tube material in the form of titanium. The properties are found in Table 4.

| Properties                        | Water vapor (fluid) | Titanium (solid) |
|-----------------------------------|---------------------|------------------|
| Density ($\frac{kg}{m^3}$)        | 0.0646              | 4500             |
| Specific Heats (Cp) ($\frac{J}{kg.K}$) | 1890                | 524              |
| Thermal conductivity ($\frac{W}{m.K}$) | 0.021               | 21.8             |
| Viscosity ($\frac{kg}{m.s}$)      | 974 $10^{-6}$       |                  |

2.2.3 Control and Monitoring Solution

The solution control used for the pressure velocity coupling method is SIMPLE with second-order upwind discretion for all parameters. In the monitoring solution, residual criteria are set for all parameters of $10^{-4}$, except for energy of $10^{-6}$.

2.3 Calculation of Heat Transfer Coefficient

The type of flow can be searched by knowing the $Re_D$

$$Re_D = \frac{\rho x V_{max} x d}{\mu} \quad (1)$$

After finding the price of $Re_D$ it can be known Prandtl number, so it is able to calculate nusselt number.

$$N_{ud} = C_1 Re_D^m Pr^{0.36}Pr^{\frac{1}{2}} \quad (2)$$

After that can be calculated the value of the coefficient of heat transfer convection outside the tube.

$$h_0 = \frac{N_{ud} x k}{D} \quad (3)$$

3. Results and Discussion

From modeling and numerical simulation obtained qualitative data in the form of contour visualization of the flow. In this case research, qualitative data analysis will be conducted, including contour visualization and analysis of the contours of velocity, temperature, and pressure on each variation and accompanied by quantitative data in the form of graph plots.

3.1 Validation

Figure 3 is a validation graph using error comparisons $Nu_D$ calculations and simulations. In the validation graph above, the simulation lines do not deviate far from the analytical calculation lines.
Figure 3. Validation of $N_u D$ calculation against $N_u D$ simulation

In the Table 5 above, it is known that the validation result does not have too far deviation between the calculation value and the simulation or has a trend of small error values below 5%. Thus the validation that is done can be said to be appropriate.

| Velocity (m/s) | Nusselt Number | % Error $N_u D$ |
|---------------|---------------|----------------|
|               | Calculation   | Simulation     |               |
| 7.07          | 91.03         | 93.07          | 2.19%         |
| 9.07          | 105.71        | 107.56         | 1.72%         |
| 11.07         | 119.14        | 121.02         | 1.55%         |

3.2 Effect of gap ratio on flow characteristics

In this research, qualitative data analysis will be carried out, including contour visualization and analysis of the velocity, temperature, and pressure contours for each variation accompanied by quantitative data in the form of graph plots.

3.2.1 Comparison of velocity contours of each variations

In Figure 4, it is the maximum velocity graph (Vmax) achieved on each variation. On the chart, the highest Vmax value is seen in the Gap Ratio variation of 1.7 with a Vmax value of 83.22 m/s, then decreases with the increase in the Gap Ratio, at a variation of 2 = 47.24 m/s, at a variation of 2.7 = 25.83 m/s, and the lowest Vmax value at a variation of 3.2 of 21.11 m/s. Vmax occurs when the flow passes through the upper tube gap and the bottom tube, the fluid flow will flow faster when it passes through a narrower gap. The influence of the extent of the gaps that the flow passes through causes Vmax differences between variations. In variation 3.2, the area of the upper tube and bottom tube gap areas passed by the flow tends to be large and continue to narrow as the Gap Ratio decreases. The smaller the Gap Ratio, the greater the maximum velocity value. Vmax indicates that many fluids make contact with the tube wall.
Figure 4. V max comparison chart of each variation.

Figure 5, the velocity distribution on the model shown by the color spectrum on the flow contour. On contours with red color spectrum have the highest velocity value, while contours with blue spectrum have a low-velocity value. In all models, it appears that the flow distribution accelerates or reaches maximum velocity when the flow crosses the gap of the upper tube and the bottom tube. The minimum flow velocity is at least 0 m/s when at the front parallel of the tube with a dark blue spectrum. This part is where the flow has no momentary velocity because it is a point of stagnation. The point of stagnation is the part that is blocked right parallel to the tube. Furthermore, on the back of the tube the velocity decreases to reach a value of 0 m/s due to the flow undergoing [11].

Figure 5. Velocity contours of each variation: (a) s/d = 3.2, (b) s/d = 2.7, (c) s/d = 2, (d) s/d = 1.7.
### 3.2.2 Comparison of temperature contours of each variations

Figure 6 is an outlet temperature chart on each variation that is the result of fluent iteration. On the chart, the highest outlet temperature value is in the Gap Ratio variation of 3.2 with a temperature value of 315.98 K, then decreased with the decrease in Gap Ratio, at a variation of 2.7 = 315.26 K, on a variation of 2 = 312.84 K, and the lowest outlet temperature value at a variation of 1.7 of 310.66 K. It shows that the smaller the Gap Ratio the maximum heat transfer that occurs. However, looking at the trend chart on variations 3.2 and 2.7 outlet temperature difference is very small because, in both variations, there is equally a free area between the upper tube and the bottom tube. The flow does not intersect much with the tube in these variations, causing heat transfer that occurs not maximally.

![Figure 6. Temperature outlet comparison chart of each variation.](image)

Figure 7 shows a visualization of the temperature contours on the Gap Ratio variation model with an inlet velocity of 7.07 m/s. The temperature in the steam inlet is 318.05 K. At the same time, seawater inside the tube has an average temperature of 306.35 K. Temperature distribution can be seen from the color spectrum in the contour image. On contours with red spectrum shows the highest temperature, while blue spectrum indicates the lowest temperature. It appears that the highest temperature in red is on the inlet side, while the dark blue temperature is on the wall tube side. The temperature value changes as the fluid flow through the tube. Inflow with a uniform temperature of 318.05 K, heat from the flow is absorbed by the tubes so that the flow undergoes heat transfer and the temperature on the outlet side is reduced.

Known in qualitative data outlet parts seen differences in spectrum color on each variation. In variation 3.2, the contours on the outlet are orange, indicating that the fluid still has a high temperature. The 2.7 variation yellow indicates a fluid temperature lower than the previous temperature but still tends to be high. In variation 2, green indicates a low-temperature value due to more heat transfer. Moreover, the 1.7 variation is bluish-green, which indicates a lower temperature than the previous three variations. The variation 1.7 has the lowest outlet temperature in the results of this simulation.

Figure 7 shows that the smaller the Gap Ratio, the smaller the outlet temperature produced. In the variation of 1.7 steam fluid, more hit the wall of the tube, so the chance of heat transfer is greater, and the variation gap ratio 2. While in variation 2.7, a free area is located in the middle of the upper and lower tubes. The flow is not maximally doing heat transfer with the tube, and the 3.2 variation, which has the highest outlet temperature, results in this simulation.
3.2.3 Comparison of pressure contours of each variations

Figure 8 is a graph of the influence of the gap ratio on pressure drop. The inlet side value calculates pressure drop calculation in this research minus the outlet side value. The inlet pressure is set at 7999.34 Pa with a flow velocity of 7.07 m/s, and the pressure outlet value is the result of simulated iteration. Seen the highest pressure drop value is in the variation gap ratio 1.7 with a pressure drop value of 515.99 Pa, then decreased with the decrease in the Gap Ratio, on variation 2 = 119.17 Pa, in the variation 2.7 = 21.28 Pa, and the lowest pressure drop value is in the variation 3.2 of 9.8 Pa. This indicates that the smaller the Gap Ratio, the more significant the pressure drop. This is due to the amount of friction between the flow and the surface of the tube so that in the variation of gap ratio is less chance of more friction and causes a more significant decrease in pressure.

Figure 7. Temperature contours of each variation: (a) s/d = 3.2, (b) s/d = 2.7, (c) s/d = 2, (d) s/d = 1.7.

Figure 8. Pressure drop comparison chart of each variation.
Figure 9 shows a visualization of the absolute pressure contours on the Gap Ratio variation model. On contours with the red color, the spectrum shows the highest pressure, while the blue color spectrum shows the lowest pressure. Pressure decreases after the flow passes through the tubes. The decrease in pressure in the flow can be caused by several other factors, namely the flow density, the maximum velocity of the flow, and the correction factors and friction factors that are influenced by the longitudinal, transverse, and diagonal distances of the tubes. The pressure contour indicates that the narrower the gap through the fluid causes the flow pressure in the gap decrease, accompanied by increased velocity and increased heat transfer. High-Pressure Drop will affect tube resistance.

The pressure inlet is set at 7999.34 Pa with a flow velocity of 7.07 m/s, and the pressure outlet value is the result of simulated iteration. In variation 3.2 obtained pressure outlet value of 7989.58 Pa, on variation 2.7 = 7978.08 Pa, on variation 2 = 7880.18 Pa, and on variation 1.7 of 7483.35 Pa.

![Figure 9](image.png)

**Figure 9.** Absolute Pressure contours of each variation: (a) s/d = 3.2, (b) s/d = 2.7, (c) s/d = 2, (d) s/d = 1.7.

### 3.3 Effect of Gap Ratio on Heat Transfer

In this research, the authors calculated the heat transfer coefficient and local Nusselt Number for each tube to analyses heat transfer. For local Nusselt Number, shows the distribution graph of each tube.

#### 3.3.1 Comparison of shell-side Heat Transfer Coefficient of each variation

In theory the greater the value of the convection coefficient, the better the heat transfer that occurs. Convection heat transfer occurs because the steam flow with a high temperature intersects with the tube wall with a lower temperature so that the steam temperature drops and condenses. The Nusselt Number also influences the magnitude of the convection coefficient. The larger the Nusselt number, the greater the convection coefficient that occurs. In addition, the value of the convection coefficient is also
influenced by the conductivity of thermal steam, as in equation (3). Thermal conductivity is defined as the rate of conduction heat transfer through the cross-sectional area of the material unit.

Figure 10 above shows the influence of the Gap Ratio on the convection coefficient, the value obtained from the equation (3). The largest convection coefficient value is in variation 1.7 with a convection coefficient value of 103.34 (W/m²K) then decreases with the decrease in gap ratio, in variations 2 = 76.95 (W/m²K), in variations 2.7 = 51.22 (W/m²K). The smallest convection coefficient is in the 3.2 variation of 45.38 (W/m²K). This result shows that the smaller the Gap Ratio, the greater the coefficient of heat transfer. The smaller the Gap Ratio, the more often it intersects with the tube wall and the chance of a large heat transfer resulting in increased heat transfer coefficient values.

![Figure 10. Graph of the effect of Gap Ratio on shell side heat transfer coefficient](image)

3.3.2 Comparison of local Nusselt number of each variations

Local Nusselt Number is a heat transfer ratio calculated using the local heat transfer coefficient based on local heat flux and local temperature at the tube surface. Each start of a new variation requires a different Tref input [12]. However, certain cases cannot be done in fluent. Therefore, the local Nusselt number is only an indication of the actual condition expression. The local Nusselt number value that is graphed only shows qualitative. This means the local Nusselt number in fluent has a trend chart only. The average Local Nusselt Number comparison of each variation is presented in Figure 11. it can be seen that the highest average Local Nusselt Number is achieved with a gap ratio of 1.7. Furthermore, with the increase of Gap Ratio, the local Nusselt number on average is also decreasing. Because the turbulent flow passes through the surface, the local Nusselt number is higher. The smaller the gap, the higher the flow velocity. With high velocity, the Local Nusselt Number will be even bigger.

![Figure 11. Local Nusselt number comparison chart of each variation.](image)
To observe the distribution of Local Nusselt Number carried out the plot with data retrieval in Figure 12. Data retrieval is performed on tubes 1, 2, and 4 at angles of 0°-180°.

Figure 12. Location of data retrieval.

Figure 13 is a local Nusselt number distribution chart on tube one at an angle of 0°-180°. Trend lines are symbolized by several different colors per variation, Red lines are variations of 3.2, green lines = variations 2.7, blue lines = 2 variations, orange lines = 1.7 variations.

All variations at the time of θ = 0° have the same Local Nusselt Number value, on the trend line (a) and (b) is the maximum local Nusselt number that occurs because it is a stagnation area at that angle. As the thermal boundary layer flows on the trend line (a) and (b), the Local Nusselt Number value heads towards the minimum value when it is at the separation point at an angle of about θ = 120°. While on the trend line (c) and (d) experienced an increase in the local Nusselt number value at an angle of about θ = 90° until then experienced a minimum value at the separation point around the angle of 120° < θ < 150°. The increase in the value at θ = 90° is due to the flow through a narrow gap, and turbulence occurs. The heat transfer that occurs increases until finally, the value decreases when it is at the separation point. Then after the separation point, the value of the Local Nusselt Number increased due to turbulent intensity near the tube wall in the area after the separation also increased. This condition allows the coefficient of heat transfer to increase, which then causes the Local Nusselt Number value to rise.

On-trend lines (a) and (b), the angle of θ = 180° of the Local Nusselt Number value reaches the minimum. When viewed from the temperature contour at the corner point θ = 180° stagnation area behind the tube and in the variation is seen heat transfer that occurs tends to be small because the flow through the tube without being blocked by a narrow transverse gap so that the fluid flow does not turbulence and does not reach at that point. In the temperature contour detail, the blue spectrum color on the tube wall reaches outside the wall boundary so that there is no good heat transfer at that point.

Figure 13. Local Nusselt number distribution comparison chart in tube1 of each variation: (a) s/d = 3.2, (b) s/d = 2.7, (c) s/d = 2, (d) s/d = 1.7.

Figure 14 shows Local Nusselt Number distribution on tube 2 starts at stagnation point and goes to the maximum value as the thermal boundary layer grows. Maximum value occurs because, in that part,
the flow intersects with the tube wall without any obstructions, thus allowing the coefficient of heat transfer to increase and cause the Local Nusselt Number value to be maximum. As with tube 1, there is a decrease in value at the separation point in all variations and an increase in return after passing the separation point due to the flow mixing so that vortexes form which causes the coefficient of heat transfer to increase [13].

The maximum Local Nusselt Number value obtained at about $30^\circ < \theta < 60^\circ$ is the largest value compared to other angles due to the fluid flow is more chaotic when passing through the gap between the upper and lower tubes so that the maximum Local Nusselt Number value on the side of the angle of $30^\circ < \theta < 60^\circ$ tube is 2nd. Similarly, it happens on the 3rd and 4th tubes but not as much as the value on the 2nd tube because the flow has passed through several tubes and has decreased the fluid temperature.

Figure 14. Local Nusselt number distribution comparison chart in tube 1 of each variation: (a) s/d = 3.2, (b) s/d = 2.7, (c) s/d = 2, (d) s/d = 1.7.

Figure 15 shows the Local Nusselt Number distribution graph on tube 4. A similar trend line between the 4th and second tubes starts at the stagnation point and goes to the maximum value as the thermal boundary layer grows; there is a decrease in value at the separation point and increases again after passing the separation point.

Figure 15. Local Nusselt number distribution comparison chart in tube 4 of each variation: (a) s/d = 3.2, (b) s/d = 2.7, (c) s/d = 2, (d) s/d = 1.7.
4. Conclusion

The influence of Gap Ratio variations indicates that the smaller gap ratio will result in a higher Vmax value. In the gap ratio, variation 1.7 has the highest Vmax value of 83.22 m/s. Then the smaller the Gap Ratio results in a lower outlet temperature. The variation gap ratio of 1.7 has an outlet temperature value of 310.66 K. Then the influence of Gap Ratio variation on pressure drop shows the smaller gap ratio resulting in the highest pressure drop value. In the gap ratio variation, 1.7 has the highest pressure drop value of 515.99 Pa.

Gap Ratio variation also indicates that the smaller the Gap Ratio will increase heat transfer coefficient. The variation gap ratio of 1.7 has the highest coefficient of the heat transfer value of 103.34 W/m²K. Then, at the value of Local Nusselt Number, the average indicates the smaller the Gap Ratio increases the local Nusselt number average value. In the Gap Ratio variation, 1.7 has the highest average Local Nusselt Number value of 53.65.

Acknowledgments

The authors would like to convey their appreciation to the Politeknik Elektronika Negeri Surabaya and Institut Teknologi Sepuluh Nopember. The author also thanked to the Directorate General of Resources for Science, Technology and Higher Education; Ministry of Research, Technology and Higher Education, the Republic of Indonesia, supporting the relevant project under a scheme called Basic Research under contract number 820/PKS/ITS/2021.

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