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Numerical Study of Heat Transfer Characteristics in High Pressure Steam Turbine during Stop Unit Process with Sliding Pressure

Budi Santoso, Bambang Arip Dwiyantoro*

Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember, Sukolilo Surabaya 60111, Indonesia

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Abstract

During maintenance of the turbine and its auxiliary equipment, which requires a stop of the turbine oil system equipment and an open turbine casing, the first stage metal temperature requirement must be below 150°C. The normal stop unit method with natural cooling takes about 14 to 17 days. In order to speed up the cooling time to 5 days, a forced cooling turbine is needed using the stop unit method with sliding pressure. The heat transfer that occurs in the high-pressure turbine during the stop unit process with sliding pressure was investigated using the numerical method of CFD simulation. The 2D geometry design was made from high-pressure turbine cutouts images. Then meshing was made. The solver stage and the post-processing stage were set. The simulation was running in a steady state and followed by transients. The validation method was to compare the first stage metal temperature parameter between the actual process and the results of the CFD simulation at a load of 350 MW, then re-simulate it at 500 MW and 645 MW. The stop unit process with sliding pressure starting at 645MW resulted in the best final cooling compared to the stop unit at 500 MW and 350MW loads. By increasing the main steam flow, the resulting cooling increases. By increasing the value of the fluid flow velocity, the Reynolds number increases, so the convection heat coefficient also increases.

Keywords: First stage metal temperature, stop unit, sliding pressure

1. Introduction

Adipala Steam Power Plant, one of the power plants owned by PT Perusahaan Listrik Negara, is managed through Operation and Maintenance Services by PT Indonesia Power as its subsidiary. Adipala Steam Power Plant is located in Bunton Village, Adipala District, Cilacap Regency. PT Perusahaan Listrik Negara as asset owner and PT Indonesia Power as asset manager. Adipala Steam Power Plant has an installed power capacity of 1 x 660 MW using low-rank coal as fuel, with 3800-4400 kcal/kg (HHV/High Heating Value) and an average consumption of 9000 tons/day at load full 660 MW. One of the main pieces of equipment of a steam power plant is a turbine, a mechanical device that converts energy from steam into rotational motion, which is forwarded to a generator to become electricity [1–4]

Turbine maintenance work takes a long time, which is preceded by the cooling process of the turbine since it is turned off to a temperature that allows for the opening of the turbine casing. So far, the turbine cooling process takes about 14 to 17 days, following the standard operating procedure set by the turbine manufacturer. A faster cooling method that ranges from 3 to 5 days is known as the turbine-forced cooling method. Three commonly used methods are the stop unit method with sliding pressure, external steam cooling, and air cooling [5]. External steam cooling and air cooling methods are common in various Steam Power Plant in Indonesia [6–8]. But for the stop unit method with sliding pressure, this is the first time it has been carried out at Adipala Steam Power Plant from all Steam Power Plant managed by PT. Indonesian Power. Adipala Steam Power Plant has done the stop unit method with sliding pressure twice on 6 January 2020 and 19 June 2021.

For this reason, this study examines the forced cooling turbine process using the stop unit method with sliding pressure which has never been discussed in any research journal. All existing research on forced cooling turbines uses the post-stop turbine air cooling method. This study aims to determine the characteristics of flow and heat transfer in the high-pressure turbine during the stop unit process with sliding pressure, get the most optimal high-pressure turbine cooling results from the simulation carried out, and determine the comparison of the stop process time unit with sliding pressure when compared to normal stop unit process with natural cooling.

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*Corresponding author. Email: bambangads@me.its.ac.id.

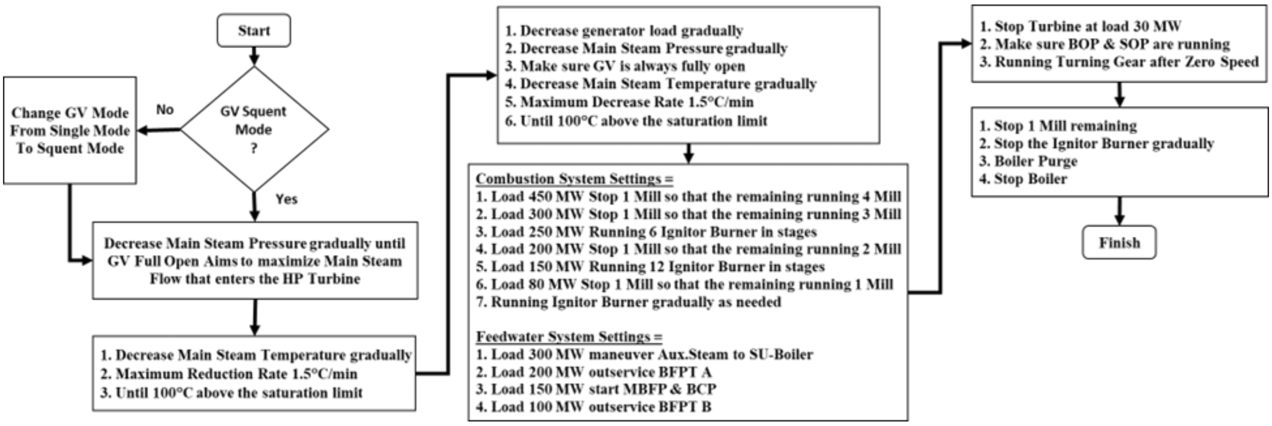


Figure 1. Flowchart of stop unit process with sliding pressure.

2. CFD Simulation Method

2.1. Stop Unit Process with Sliding Pressure

The sequence of steps carried out in the stop unit process with sliding pressure [9], as shown in Figure 1, was to lower the main steam pressure and temperature as low as possible with four governor valves opened 100% in sequence control mode. The unit load was reduced gradually, and the main steam pressure and temperature were lowered below the normal operating limits. As a note that must be considered, the decrease in the main steam temperature rate should not exceed the safe limits. Ensured that the steam entering the turbine was still in the superheat phase within the main steam pressure and temperature parameters.

The first stage metal temperature was checked when the load reached 50 MW to see if it had reached $< 300°C$. If so, the load was lowered to 30 MW. Then, the gas circuit breaker was opened. With this condition, the boiler and turbine were still operating, but the generator had disconnected from the 500 kV network. The rest of the boiler combustion lowered gradually but ensured that the steam entering the turbine was still in the superheat phase. Steam from combustion at a low boiler load was utilized for turbine cooling. When the first steam metal temperature had reached $< 271°C$ or the steam entering the turbine phase was approaching saturation, stopped the turbine and the boiler.

2.2. High-Pressure Turbine Geometry Design

Figure 2 showed the Adipala supercritical steam power plant turbine through a side view. Figure 2 represented the overall construction of the Adipala supercritical steam power plant turbine. There were high-pressure turbines, intermediate-pressure turbines, low-pressure turbines A, and low-pressure turbines B.

From Figure 2, the geometry modeling took only a part of the side view of the high-pressure turbine, as shown in Figure 3(a) [10]. Only the upper side of the high-pressure turbine was used because it represented the general description of the high-pressure turbine, as shown in Figure 3(b) [10].

After simplifying the image, as shown in 3(b), geometric modeling was performed using Space Claim in 2D dimensions based on the planned dimensions shown in Figure 4. Geometry simplification was carried out to simplify the flow channel to focus this research on the effect of temperature on the solid part.

2.3. Simulation Design

The neat and tight meshing process was also a requirement in simulations with thermal effects on the standard $k - \epsilon$ model. Some geometries had undergone a meshing process, as shown in Figure 5(a). In this study, meshing was carried out with the number of cells 665160 and nodes 672709, with the mesh face element being a hybrid between tri/quad. The quality of the mesh was checked through the quality option.

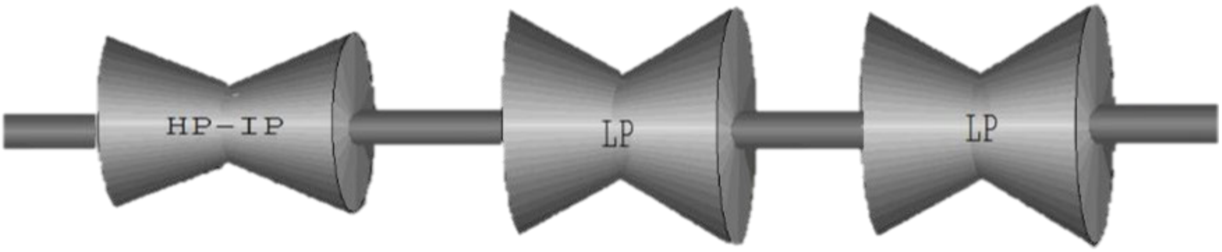
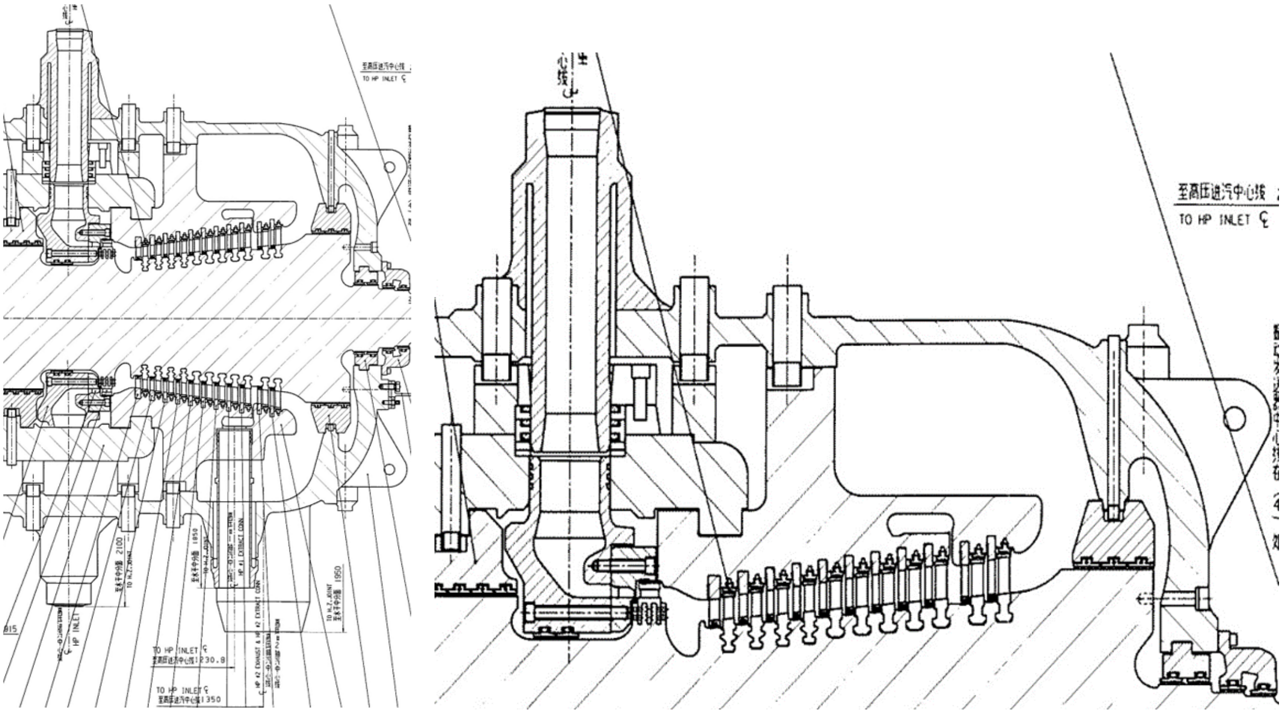


Figure 2. Classification of the Side View of Adipala Supercritical Steam Power Plant Turbine.



(a) Side view.

(b) 2D simulation geometry modelling.

Figure 3. HP turbine section [10].

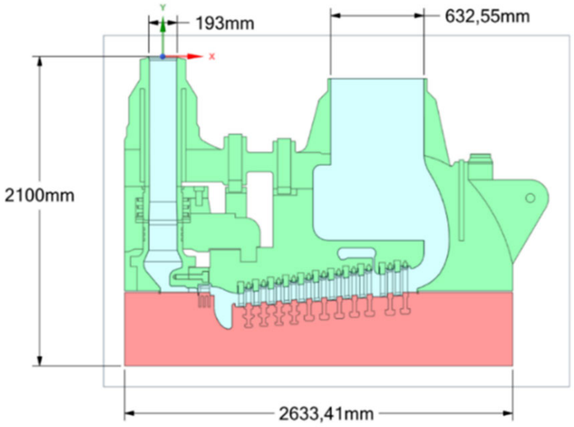


Figure 4. 2D Model of analyzed geometry.

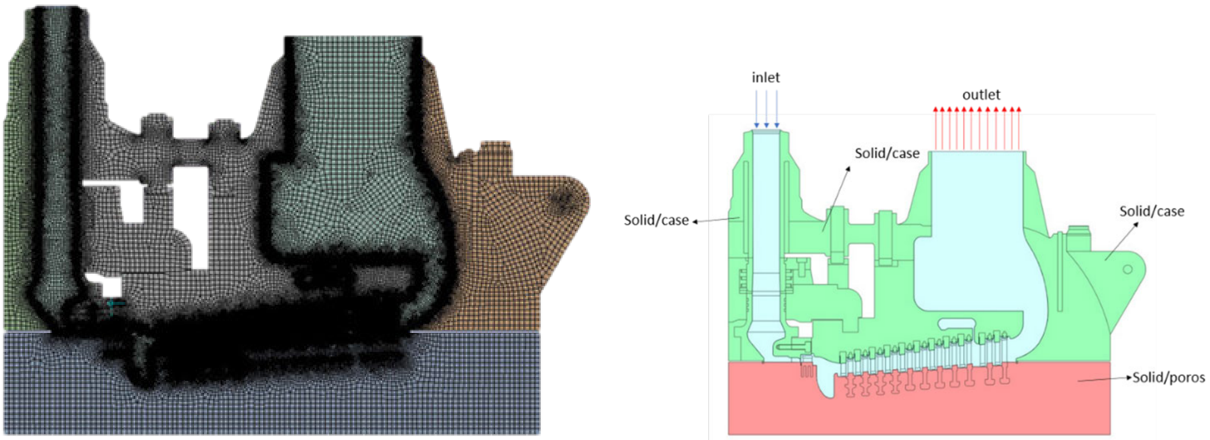
The maximum skewness obtained was 0.91, which was still within the acceptable limits in the skewness matrix.

After the pre-processing stage by creating geometry and meshing, the next step was selecting a solver before calculating the running iteration. Based on these considerations, 2D and Double Precision were selected in this solving stage to obtain more accurate results. The solver model was a pressure-based and absolute velocity formulation. In this simulation, the dual solver method was used from steady simulation and changed to transient in the middle of the simulation to start the sliding pressure process. In this design, $k-\epsilon$ (2 eqn) was used with the standard wall function, and the model constant was not changed (defaulted). The type of material was steam (water vapor) and solid.

The boundary condition, as shown in Figure 5(b), was one of the most important stages of the solver, where the necessary data was input before running the simulation. At this stage, the simulation was set according to the variations applied and the expected output requirements. Then, boundary conditions were set to the model: a. Fluid-solid contact wall was defined as interface coupled-wall; b. Inlet was defined as velocity/mass flow; c. Outlet was defined as pressure outlet; d. Solid non-contact fluid wall was defined as wall.

The steady-state simulation was carried out at initial conditions (t = 0 hr). After steady iteration results, the parameters at the inlet and outlet were changed according to Table 1 to start the transient sliding pressure simulation process. The transient simulation process was carried out by changing the time to transient and then changing the parameters of the inlet and outlet conditions at the first step stamp representing the middle condition of the sliding pressure process. After the simulation ran for 30 minutes in the next time step, the parameters of the inlet and outlet conditions were changed to parameters in the second time step stamp, representing the final condition of the sliding pressure process.

Solution control had several optional parameters that needed to be entered before running the iteration to obtain convergent results and simulation results that are



(a) Meshing.

(b) Boundary condition.

Figure 5. Design modelling.

close to actual. Pressure velocity was selected coupled because it was suitable for the flow of complex shapes and turbulence. Discretization was all second-order upwind with consistent considerations in calculating flux flowing through the cell surface. The coefficient of discrete equations was always positive to fitted the needs and displayed the flow direction. The choice of solution method and solution control under steady and transient conditions was the same.

In the transient calculation process, a time advancement type fixed user-specified method was used with a time-step parameter of 0.25 seconds and a number of iterations per time step of 20 iterations.

2.4. Numerical Study Simulation Variation Data

Variation data on high-pressure turbine steam parameters included pressure, temperature, and flow, representing conditions in variation 1. Initial data simulation was modeled into three steps representing the sliding pressure process initial, middle, and final conditions. So the heat transfer phenomena that occur in the high-pressure turbine could be known.

After the initial simulation modeling was completed, variations 2 and 3 were re-simulated. Each variation simulated by sliding pressure in 3 steps representing the initial (t = 0 hr), middle (t = 6 hr) and final (t = 10 hr) conditions. In the early stages (t = 0 hr), it was simulated in a steady state, while in the middle (t = 6 hr) and final stages (t = 10 hr), each transiently simulated for 12 steps using 300 seconds per step so that the total time required was 3,600 seconds.

3. Results and Discussion

3.1. Preliminary Design Results of CFD Simulation

The initial design of the CFD simulation uses data from the stop unit process with sliding pressure with a

Table 1. Variation of main steam parameter data with sliding pressure method.

Name	Unit	Steady State	Transient	
		Beginning	Middle	End
		t = 0 hr	t = 6 hr	t = 10 hr
Variation 1 (Load 350 MW)				
Main Steam Pressure	Mpa	16.81	8.15	1.5
Main Steam Temperature	°C	568.1	398.2	309.7
Main Steam Flow	Ton/hour	1096.8	688.6	163.9
Variation 2 (Load 500 MW)				
Main Steam Pressure	Mpa	23.5	10	1.5
Main Steam Temperature	°C	570	440	309.7
Main Steam Flow	Ton/hour	1615	875	163.9
Variation 3 (Load 645 MW)				
Main Steam Pressure	Mpa	24.2	12.2	1.5
Main Steam Temperature	°C	570	450	309.7
Main Steam Flow	Ton/hour	1950	1090	163.9

Table 2. Data for variation 1 (Load 350 MW).

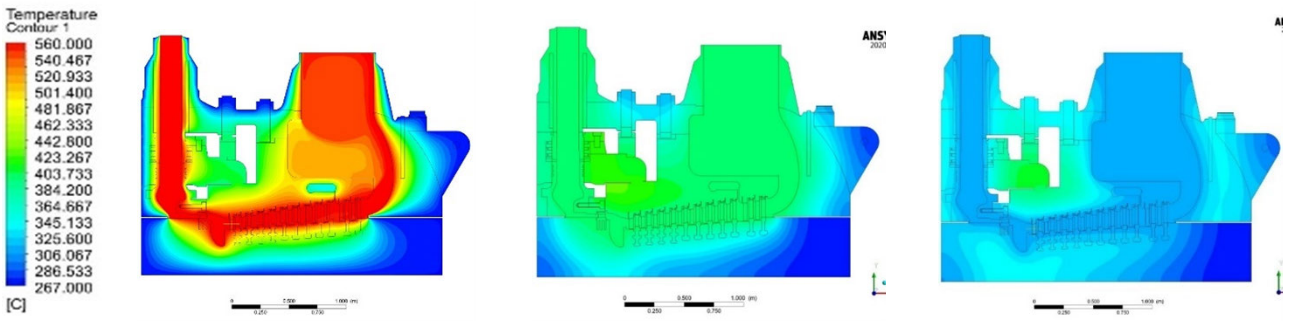
Variation 1 (Load 350 MW)				
		Steady State	Transient	
Name	Unit	Beginning	Middle	End
		t = 0 hr	t = 6 hr	t =10 hr
Main Steam Pressure	Mpa	16.81	8.15	1.5
Main Steam Temperature	°C	568.1	398.2	309.7
Main Steam Flow	Ton/hour	1096.8	688.6	163.9
Simulation Results Variation 1 (Load 350 MW)				
First Stage Metal Temperature	°C	506.2	384.2	309.7

load prefix of 350 MW, also known as variation 1, which is carried out through an experimental process at the plant. The simulation results, which are the first stage metal temperature, are shown in Table 2. The contour temperature is shown in Figure 6, the contour pressure is shown in Figure 7(a), and the streamline velocity is shown in Figure 7(b).

Figure 6 shows a decrease in temperature in the fluid path and the solid plane following the stop unit process with sliding pressure in the early, middle and final stages. The decrease in temperature in the solid field, namely the casing and shaft of the high-pressure turbine, occurs due to the influence of the temperature of the steam flowing into the high-pressure turbine, which is initially high and then continues to decrease until the end of the process. Figure 7(a) shows that the pressure drop at the nozzle and level 1 blade (impulse blade) is converted into an increase in speed, as shown in streamline velocity in Figure 7(b). This pressure drop and velocity increase follow the characteristics of the turbine impulse blade shown in Figure 7(c). In the stop unit method with sliding pressure, the first stage metal (level 1 blade) is flowed by high-speed steam with a larger flow rate and a lower temperature than the nominal value of its operation. So over time, the sliding pressure accelerates the cooling in the first stage metal area (blade level 1).

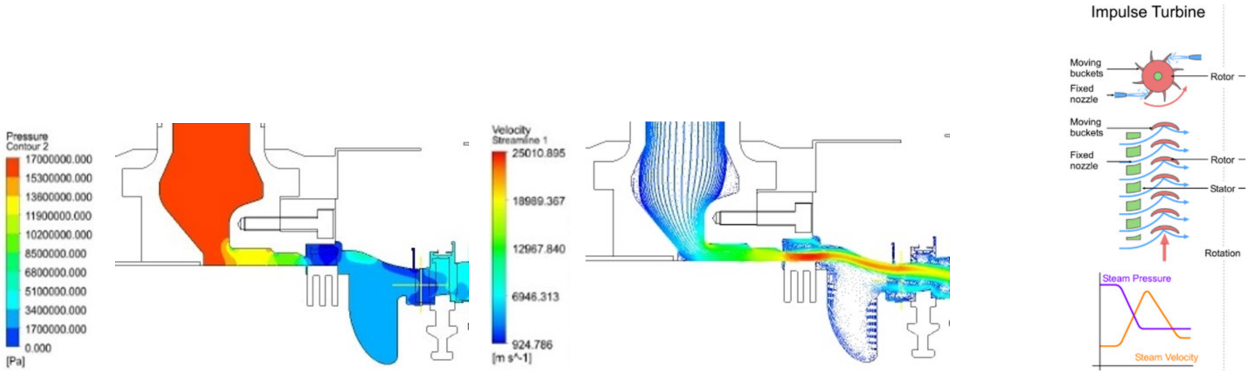
3.2. Validation of CFD Simulation Modelling Results

The method used for validation is to compare the first stage metal temperature data from the stop unit pro-



(a) Beginning-process. **(b)** Mid-process. **(c)** End-process.

Figure 6. Contour temperature in the high-pressure turbine during the sliding pressure process at a load of 350 MW.



(a) Contour pressure. **(b)** Streamline velocity. **(c)** Impulse turbine blade characteristics.

Figure 7. The high-pressure turbine at the beginning of the sliding pressure process at a load of 350MW.

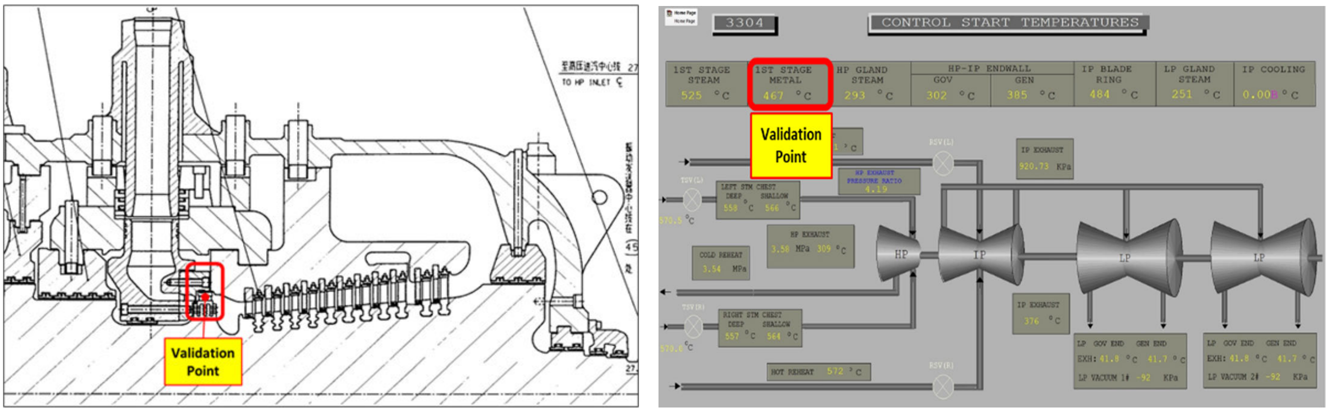


Figure 8. The point used as validation.

cess with sliding pressure carried out through an experimental process in the generator with the data from the CFD simulation at the same point of the collection, as shown in Table 3. The validation point is shown in the area in the red box, as shown in Figure 8. The temperature difference percentage is calculated at the beginning of the process at 0 hours, mid-process at 6 hours, and end of the process at 10 hours. Limiting the maximum percentage difference in temperature below 5% means that the CFD simulation results are assumed to be accurate to the actual process.

The percentage difference in temperature in the initial, middle and final processes is below 5%, so the CFD simulation results are accurate to the actual process. Therefore, this simulation process can be used as the basis for the next simulation process to run variation 2, which represents a load of 500 MW, and variation 3, which represents a 645 MW load. Figure 9 shows a graph to compare the first stage metal temperature data between the actual process and the results of the CFD simulation, with data taken in Table 3, which describes the initial, middle, and final stages of the stop unit process series with sliding pressure.

3.3. CFD Simulation Results in Variation 2 (500 MW) and Variation 3 (645 MW)

Contour temperature in the high-pressure turbine during the sliding pressure process from CFD simulation at a load of 500MW, or variation 2, is shown in Figure 10. Figure 10(a) shows the beginning of the process, Figure 10(b) shows the middle of the process, and Figure 10(c) shows the end of the process. The load 645MW, or variation 3, is shown in Figure 11. Figure 11(a) shows the beginning of the process, Figure 11(b) shows the middle of the process, and Figure 11(c) shows the end of the process.

Based on the simulation results with three load variations shown in Figure 6, Figure 10, and Figure 11, the stop unit method with sliding pressure aims to cool all the main parts of the turbine, such as the blades, shaft, and casing, by utilizing the steam used to rotate the turbine rotor. The steam temperature is lowered gradually by being balanced with a decrease in steam pressure. The steam remains in the form of superheat. With the flowing steam temperature slowly lowered, the main component of the turbine gradually decreases in temperature.

3.4. Analysis of Temperature Drop in First Stage Metal

The data recapitulation of the first stage metal temperature on the actual sliding pressure process and the CFD simulation results on variation 1, variation 2, and variation 3, is shown in Table 4. The CFD simulation results in variation 1, variation 2, and variation 3, used an order 2 polynomial equation to match the time of the sliding pressure process.

Table 3. Data Validation of First Stage Metal Temperature.

Name	Unit	Time (Hour)		
		0	6	10
Actual Process	°C	483.8	367.5	310.2
CFD Simulation Results	°C	506.2	384.2	309.7
Percentage Difference	%	**4.63**	**4.54**	**0.16**

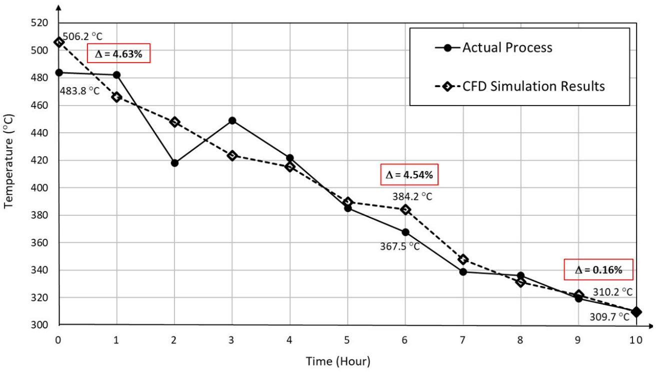
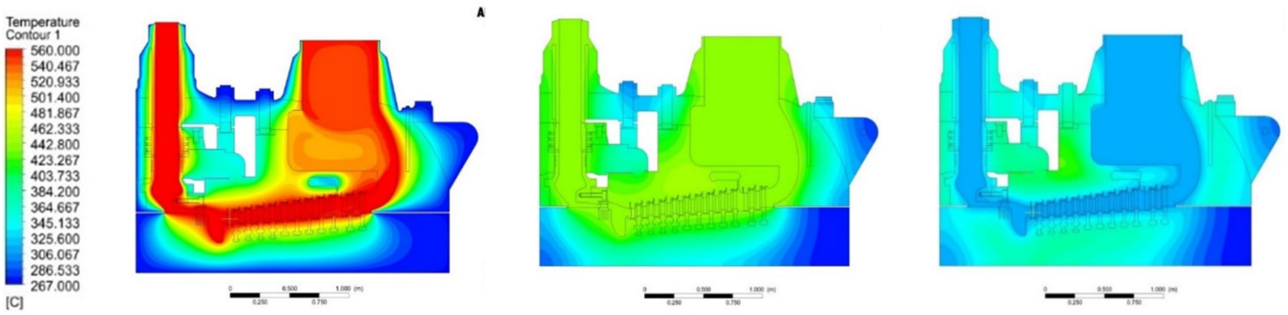
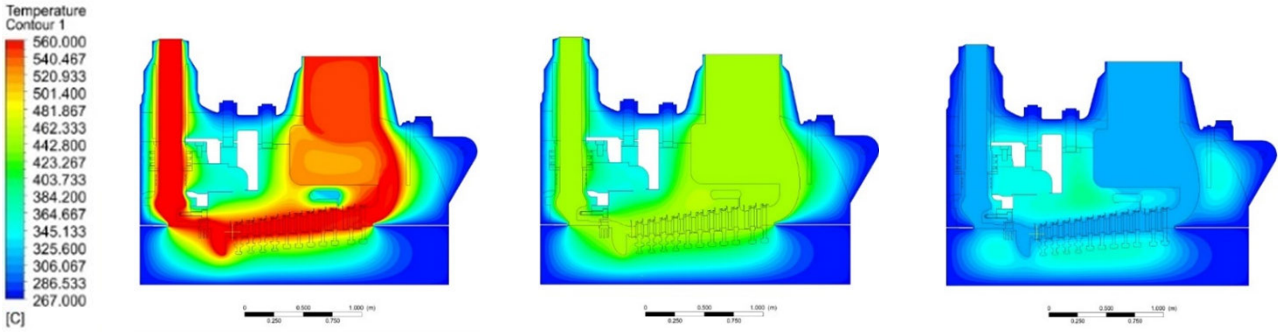


Figure 9. Graph of validation of first stage metal temperature.



(a) Beginning-process. **(b)** Mid-process. **(c)** End-process.

Figure 10. Contour temperature in the high-pressure turbine during the sliding pressure process at a load of 500 MW.



(a) Beginning-process. **(b)** Mid-process. **(c)** End-process.

Figure 11. Contour temperature in the high-pressure turbine during the sliding pressure process at a load of 645 MW.

Table 4. 2nd order polynomial equation from the variation of CFD simulation results.

Name	Unit	Process			2nd Order Polynomial Equation
		t = 0 hr	t = 6 hr	t = 10 hr	
Actual Process	°C	483.8	367.5	310.2	-
Variation 1 (Load 350 MW)	°C	506.2	384.2	309.7	$y = 23.75x^2 - 193.25x + 675.7$
Variation 2 (Load 500 MW)	°C	507.8	439.9	310	$y = -31x^2 + 25.1x + 513.7$
Variation 3 (Load 645 MW)	°C	512.2	449.7	309.8	$y = -38.7x^2 + 53.6x + 497.3$

Table 5. Temperature calculation recapitulation.

Name	Unit	Time (Hour)										
		0	1	2	3	4	5	6	7	8	9	10
Actual Process	°C	483.8	482.3	417.9	448.9	421.6	385.2	367.5	338.8	336.2	319.4	310.2
Variation 1 (Load 350 MW)	°C	506.2	482.1	460.7	439.3	419.2	401.6	384.2	361.1	341.0	323.9	309.7
Variation 2 (Load 500 MW)	°C	507.8	500.6	492.2	481.6	469.2	455.8	439.9	413.2	382.7	348.3	310
Variation 3 (Load 645 MW)	°C	512.2	507.0	500.1	490.6	478.9	465.8	449.7	422.0	389.4	352.0	309.8

Table 6. Comparison of normal stop unit and sliding pressure.

Name	Parameter	Beginning	End	Duration (Hour)
Normal Stop Unit Natural Cooling	Time	May 11, 2021 07:30 PM	May 16, 2021 00:30 AM	101
	Load	645 MW	0 MW	
	First Stage Metal	525 °C	318.4 °C	
1st Sliding Pressure	Time	Jan 05, 2020 09:00 PM	Jan 06, 2020 07:00 AM	10
	Load	600 MW	80 MW	
	First Stage Metal	518.69 °C	315.48 °C	
2nd Sliding Pressure	Time	June 18, 2021 10:00 PM	June 19, 2021 08:00 AM	10
	Load	350 MW	40 MW	
	First Stage Metal	483.8 °C	310.20 °C	

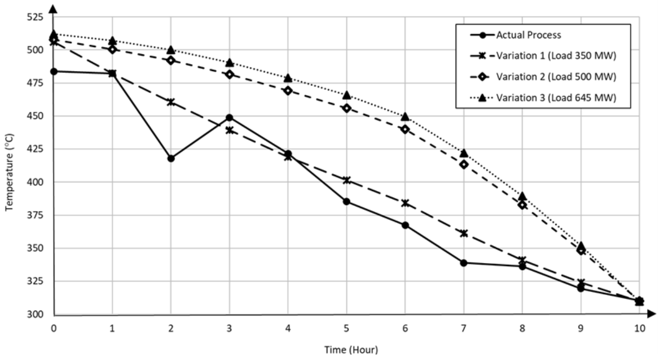


Figure 12. First stage metal temperature recapitulation graph.

Calculations using polynomial equations of order 2 for unknown temperature data are performed, namely between the initial and middle processes from the 1st hour to the 5th hour and between the middle and final processes from the 7th hour to the 9th hour. Using the polynomial equation of order 2 for unknown temperature data, it produces a graph that describes the decrease in the first stage metal temperature from 0 to 10 hours. The results of these calculations are displayed in Table 5 and visualized through the graph in Figure 12.

From Figure 12, the temperature values at the end of the process of three variations are close to each other. To see the difference in the final results of the three variations, a comparison of the contour temperature results from the CFD simulation is carried out at the end of variation 1 in Figure 6(c), variation 2 in Figure 10(c), and variation 3 in Figure 11(c). Variation 3 in Figure 11(c) shows most areas with low temperatures when compared to variation 1 and variation 2. In variation 3, when starting the stop unit with sliding pressure at a load of 645 MW, the flow of steam flowing into the high-pressure turbine is greater when compared to variations 1 and 2. By increasing the main steam flow, the resulting cooling is increased. By increasing the value of the fluid flow velocity, the Reynolds number increases, so the convection heat coefficient also increases.

3.5. Cooling Time Analysis on First Stage Metal

From 3 stop unit processes that have been carried out at the Adipala steam power plant, with the first data being the normal stop unit process with natural cooling, the second and third data being stop units with sliding pressure performed at different load prefixes, a time calculation is made with the final reference. The end first stage metal temperature at ± 300 °C. The results are shown in Table 6.

In the normal stop unit process with natural turbine cooling, the time calculation starts from the initial condition of the stop unit process until the first stage metal temperature reaches 318.4 °C takes 101 hours. Stopping the unit with sliding pressure on experimental results 1 and 2 requires the same time, which is 10 hours. Based on the cooling time of the first stage metal temperature, the stop unit process with sliding pressure is superior in terms of time speed compared to the normal stop unit process with natural turbine cooling. The stop unit process with sliding pressure flows steams with a very large flow and low temperature, which accelerates the temperature reduction in the first stage metal and other areas, such as the shaft and casing of the high-pressure turbine.

4. Conclusion

From the initial design of the CFD simulation, also known as variation 1, starting the stop unit process with sliding pressure at a load of 350 MW when compared to the actual condition, the value of the validation results at the first stage metal temperature is below 5%. So, this

CFD simulation design can be used for the next simulation process to run variation 2, which starts the stop unit process with sliding pressure at a load of 500 MW, and variation 3, which starts the stop unit process with sliding pressure at a load of 645 MW.

Variation 3, which is starting the stop unit with sliding pressure at a load of 645 MW, is the most effective to implement to get maximum cooling results in the entire area of the high-pressure turbine because variation 3 starts the process early with a large main steam flow, so the cooling process is optimal. The output is also maximal to all areas in the high-pressure turbine compared to variations 1 and 2. Therefore, the stop unit process with sliding pressure starting from a load of 645 MW is highly recommended, with fast turbine cooling for turbine maintenance.

In terms of the time required to cool the first stage metal, the process of stopping units with sliding pressure is better than normal stop units.

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