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Thermal Analyses on High and Medium Pressure Steam Flow in a Steam Conditioning Valve with a Steam Nozzle Using CFD

Helmisyah Ahmad Jalaludin[1], Muhammad Luqman Muhamad Sharifuddin[1], Mohamad Ridzuan Mohamed Rashid[1*], Mohamad Zamin Mohamad Jusoh[1]
[1]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Bukit Besi 23200 Terengganu, Malaysia.
[*]Corresponding author: mohamadridzuan@uitm.edu.my

ABSTRACT

An essential part of controlling steam flow and pressure in industrial systems is a pressure control valve which lowers and regulates steam pressure prior to its delivery process. Unplanned plant shutdowns and large operating losses could cause damage like a hairline crack near a valve diffuser on the inside surface of the control valve caused by high pressure steam. Experienced in chemical industry, a pressure control valve located in a utility area has exhibited signs of internal surface cracking might due to continuous operation in high and medium pressure steam, whereby a valve replacement is needed. This study is exploratory and not intended for quantitative prediction with a scope involving modelling of steam conditioning valve using 3D modelling software. Based on the valve specifications, the study analysed the cause of hairline crack due to steam flow within the valve using Computational Fluid Dynamics (CFD) simulation with appropriate boundary conditions in determining temperature distribution along the inner surface. The objective was to investigate the effect of temperature distribution of the valve with and without a steam nozzle at Point A-B as the hairline crack area is predicted to be initiated based on real life occurrence. The impact of flow temperature in Steam Conditioning Valve contributing to the cracking event in valve body might be due to rapid expansion of high-pressure steam, which induces cooling due to energy conversion from internal energy to kinetic energy during compressible flow. By comparing high-pressure steam (HPS) and medium-pressure steam (MPS) conditions, the nozzle inlet's pressure was reduced to compare the flow behaviour of valve under MPS condition. The overall temperature difference was significantly lower for MPS which is only 38% reduction compared with under HPS conditions of 59%. However, the temperature drop for HPS from Point A to B exhibited immediate drop compared to MPS condition which may cause cracking due to rapid cooling. The identification of critical regions with elevated temperature values, which can be related to the actual problem of chemical industry, may contribute to the ongoing MPS letdown of control valve replacement project in chemical industry.

Keywords: High Pressure; Steam Conditioning Valve; Hairline Crack; Computational Fluid Dynamics (CFD); Thermal Analyses

Abbreviations

PCV	Pressure control valve
SCV	Steam Conditioning Valve
HPS	High Pressure Steam
MPS	Medium Pressure Steam
LPS	Low Pressure Steam
CFD	Computational Fluid Dynamics

1.0 INTRODUCTION

Pressure control valve (PCV), such as Steam Conditioning Valve (SCV), plays a critical role in regulating steam flow and pressure. However, continuous operation may indicate risk of cracking in internal and external surface of the valve which may affect the efficiency and functionality of the valve in the future. It typically happens when fractures form in a pressure vessel, like globe valves. A catastrophic collapse could occur if the crack grows to its critical size under certain loading circumstances. Steam pressure is lowered and controlled by a control valve before being directed to a machine or operation. Heat exchangers, for instance, are among the key devices or procedures in the chemical industry. Depending on the process and product requirements, steam that channels through the heat exchanger works to transfer heat to the chemicals in the heat exchanger's tubing. There are three basic types of pressure that are usually used in plants or industry which are High Pressure Steam (HPS), Medium

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Pressure Steam (MPS), and Low Pressure Steam (LPS). These types of pressure are used depending on the requirement of the machine or process to achieved the desired product or result [1-2].

In chemical industry scenario, there is pressure control valve in utility area that has a hairline crack inside of the surface of the control valve near the valve diffuser based on the Non-Destructive Testing Aerosol of inner surface of the steam conditioning valve which is viewed from the above of the valve as shown in Fig. 1. The inner diameter surface of the valve body connected to the HPS to MPS letdown steam line was apparently found to have several cracks. At the top position of the circumferential weld joint joining the pipe to the valve body, the pipe segment downstream of the valve showed leakage. The body valve portion's straight line was repaired. However, there is a tiny break in the valve's interior close to the valve diffuser that needs to be replaced because it cannot be fixed. The replacement was required because these issues could result in an unscheduled plant shutdown due to possible leaks, which would cost money.

Rapid cooling and heat localisation on the inner surface of the steam conditioning valve caused the cracking issue, according to the study and report of the cracking issues completed by the inspection and project team. The impacted valve was inspected using a variety of techniques, including magnetic particle examination, ultrasonic testing, and flow detection. The team came to the conclusion that rapid cooling and heat localisation on the inner surface of the steam conditioning valve were, in fact, the cause of the cracking issues in the valve based on the results of these tests and further study. Several inspection methods were performed on the affected valve such as Ultrasonic Testing Flow Detection test, Magnetic Particle Inspection and etc. Based on the findings from these tests and subsequent analysis, the team concluded that the cracking problems in the steam conditioning valve were indeed caused by rapid cooling and heat localisation of the valve's inner surface. Thermal cyclic load and rapid temperature change on the surface of the pipe or valve are due to a sprayed boil feed water from the nozzle in pressure letdown process as the nozzle functions to convert high-pressure energy into high-velocity kinetic energy instead of transforming pressurized water into a focused jet to remove contaminants, coatings, and debris. Depending on the requirements and settings, the nozzle will spray boiling feed water based on the pressure letdown procedure. Thermal cyclic load phenomena can be caused by variations of temperature and pressure across the valve's surface as well. Thermal stress is imposed by each heating and cooling cycle because valve components contract or expand unevenly. During the pressure letdown process, the valve or pipe may be subjected to alternating flows of hot and cold fluids in HPS systems or chemical operations. These fluctuations cause expansion and contraction of the valve materials, which over time can lead to risk of fatigue, wear, and even failure if not properly designed or maintained [3-6].

This study is an exploratory and not intended for quantitative prediction involving validation of the temperature swing of the room temperature to the 1000ºC and then cooling back to the room temperature which affects the material degradation condition of the specimen or surfaces that is led by thermal cyclic load. This thermal cyclic load is one of the main contributors to the cracking formation of the specimen's surfaces. The primary objective of this study is to investigate the effect of temperature distribution of the valve with and without a steam nozzle at Point A-B as the hairline crack area is initiated based on real life occurrence. By examining the thermal variations, the evaluation may help to identify potential failure points and provide insight into how temperature-related stresses contribute to long-term degradation of the valve. Ultimately, these findings can guide improvements in design, material selection, and operating strategies to enhance the valve's reliability and lifespan.

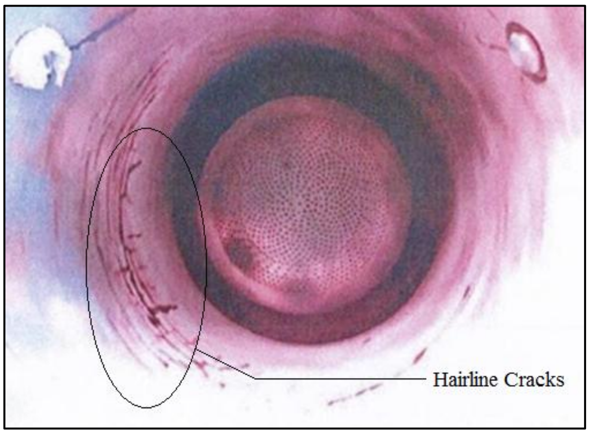


Figure 1. Non-Destructive Testing Aerosol on Inner surface of Valve

2.0 METHODOLOGY

2.1 Three-Dimensional Modelling

This study focuses on investigating the heat distribution occurring on the inner surface of a steam conditioning valve, which has been identified as a major contributing factor to cracking issues within the system. Based on Fig. 2, the flowchart indicates the workflow of this research study. The initiation of this research study is related to problems found in oil and gas industrial environments.

As seen in Fig. 3, a three dimensional design model of the Fisher CVX steam conditioning control valve (SCV) is created using SolidWorks 2025 software to aid in this problem; thus, to accurately depict the behaviour and geometry of the valve under actual operating conditions. Apart from the design phase, the study also uses Ansys 2024 (Fluent) to perform Computational Fluid Dynamics (CFD) simulations. The valve model is analysed based on the given specifications, as outlined in Table 1 to evaluate how temperature distributions behave during operation. These simulations are essential for visualizing flow characteristics and identifying regions that may be exposed to excessive thermal or mechanical stress.

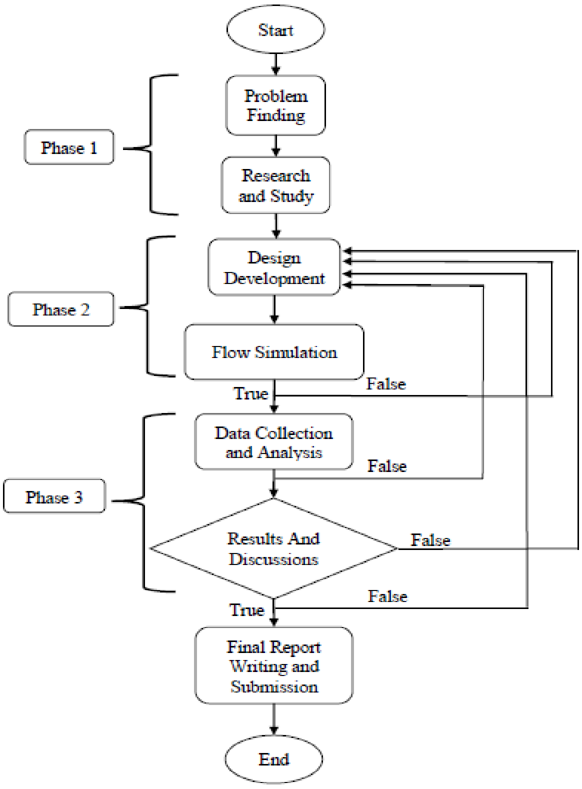


Figure 2. Flow Chart of Research Methodology

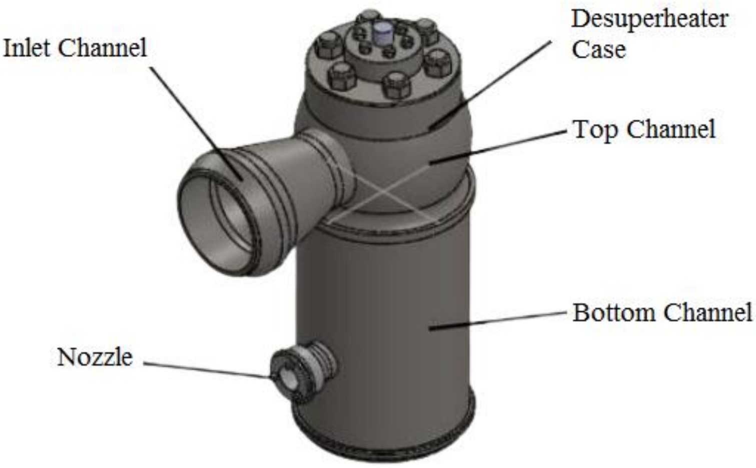


Figure 3. 3D Model of Steam Conditioning Valve

Several internal dimensions in the general arrangement drawing were not provided by the vendor. Consequently, several well-informed assumptions regarding the internal geometry and structural characteristics are made. These include particular chamfer and fillet measurements, the thickness of the desuperheater shell, and the curvature of interior surfaces. In order to keep the model realistic and appropriate for analysis, these assumptions were carefully chosen based on observable engineering and geometry judgement, despite the fact that they introduce certain constraints. Overall, the scope of this study encompasses model development, CFD simulation, and heat distribution assessment, while acknowledging necessary assumptions due to incomplete dimensional specifications [13].

Table 1: Steam Conditioning Valve Specifications

Type	Unit	Specification
Valve Model		CVX-175-CA-FSB-N1
Valve Brand		Fisher
Valve Type		Steam Conditioning Valve
Body Material		SA 182 Gr F11 (Cr-Mo Alloy)
Overall Height	(m)	1.493
Valve Inlet	Dimension (Inch)	12 in NPS
	Temperature (ºC)	430
	Pressure (Barg)	50
Valve Outlet	Dimension (Inch)	18 in NPS
	Temperature (ºC)	280
	Pressure (Barg)	17.2
Nozzle	Dimension (Inch)	3
	Temperature (ºC)	108
	Pressure (Barg)	48

2.2 Grid independence and numerical validation

The simulation analysis was carried out using Ansys 2024 (Fluent). The process begins with importing a 3D model from geometric modelling software followed by simulation analysis to analyse thermal behaviour on the surface of valve body. It is because temperature distribution across the inner surface of the valve can be evaluated from this flow simulation. Firstly, each part of the 3D model design of Steam Conditioning Valve (SCV) was combined into one solid object to ease up the meshing process afterward in Spaceclaim geometry. After each part was combined, the volume inside of the valve was extracted from the main valve's body and then the valve's geometry was deleted because flow simulation only happens in volume inside of the valve. The model underwent meshing process using a tetrahedron element type because of its ability to handle complex and irregular geometries.

To ensure the reliability and accuracy of the CFD simulations for the steam conditioning valve, a grid independence study and numerical validation were performed. Three progressively refined meshes of coarse, medium, and fine meshes were generated for the valve and nozzle geometry, with particular refinement applied near the nozzle region and valve throat where high velocity and thermal gradients are expected due to the high-pressure steam inlet which are 50 barg and high temperature of 430ºC, and rapid expansion. Key output parameters including temperature distribution was monitored. The comparison showed that significant variation was observed between the coarse and medium meshes. The difference between medium and fine meshes was less than 1-2% for temperature and pressure drop. This indicates that the solution reached mesh independence, and the fine mesh was selected for further simulations. Similar studies have reported that grid refinement leading to changes below 1% in key thermal or flow parameters is sufficient to ensure mesh-independent solutions [15]. Additionally, grid independence is essential to eliminate discretization errors and ensure that numerical predictions are not influenced by mesh size [16]. The body sizing with 0.01 m element size was applied to the volume geometry for more refine and smooth mesh surface finish as shown in Fig. 4. After the meshing was done, each of the interacted surface such as inlet valve, inlet nozzle, outlet valve and wall was named selection for easier setup when in Fluid Flow Fluent Setup procedure. Validation of the CFD model was conducted by comparing simulation results with theoretical and published data for compressible steam flow through nozzles and valve systems. The predicted pressure drop and temperature trends across the valve from 50 barg to 17.2 barg and 430ºC to 280ºC showed good agreement with expected thermodynamic behaviour of expanding steam. Previous studies have emphasized that CFD simulations must be validated against experimental or reference data to ensure predictive capability, particularly for pressure loss and thermal characteristics [17]. Furthermore, validated CFD models of steam flows in nozzles have demonstrated strong agreement with experimental measurements, confirming their applicability in high-pressure thermal systems [18].

Figure 4: Meshing Setup on the 3D Modelling

2.3 Flow Simulation and Data Acquisition

The temperature of the choice of material, the intake and outflow, and other valve parameters were set up as boundary conditions. Each interacting surface including the wall, output valve, inlet nozzle, and inlet valve was given a selection after the meshing process to make the fluid flow setup process easy. Since many real-world fluid and thermal behaviour phenomena are time-dependent and cannot be adequately represented by steady-state assumptions, transient time setup was used after the meshing setup was completed and updated. Energy was applied to insert the temperature for the nozzle inlet and nozzle outlet. Realizable with scalable wall function of k-epsilon model was used in complicated flow simulation because it offers a good balance between rotation, accuracy, numerical stability, and computational efficiency particularly for flows involving strong turbulence, separation, and complex geometries as shown in Table 2. Water vapor was set in cell zone condition that will act as medium in the flow simulation.

High Pressure Steam Condition (HPS) and Medium Pressure Steam Condition (MPS) are the two steam pressure conditions used in the simulation. Based on real-world industrial scenarios, the pressure applied to the HPS condition valve inlet is 50 Bar(g), or 5,000,000 Pa, and the temperature is set at 430°C. As indicated in Fig. 5 and Table 3, the temperature was fixed at 280°C and the pressure applied to the nozzle inlet was 48 Bar(g), or 4,800,000 Pa, while MPS condition, valve inlet and pressure applied based on actual scenario in industry is 30 Bar(g) which is equivalent to 3,000,000 Pa and temperature set on 430°C. As indicated in Table 4, the temperature was fixed at 108°C and the pressure applied to the nozzle inlet was 25 Bar (g), or 2,500,000 Pa. A coupled system with a second order setup was employed in the methods setup. This is because, particularly in cases where flow physics are highly interconnected, it offers improved numerical stability, quicker convergence, and more precise coupling between governing equations. The system was initialised using hybrid initialisation following the completion and verification of all fluent setup. After the initialisation was completed, the calculation was run using 20 number of time steps with 1s step size and maximum iterations was set on 50 until the simulation was stabilised. When the calculation converged, the result of temperature distribution was recorded and analysed.

Table 2: Boundary Conditions Setup for k-epsilon (2 eqn) Model

Item	Value
C2-epsilon	1.9
TKE Prandtl Number	1
TDR Prandtl Number	1.2
Energy Prandtl Number	0.85
Wall Prandtl Number	0.85

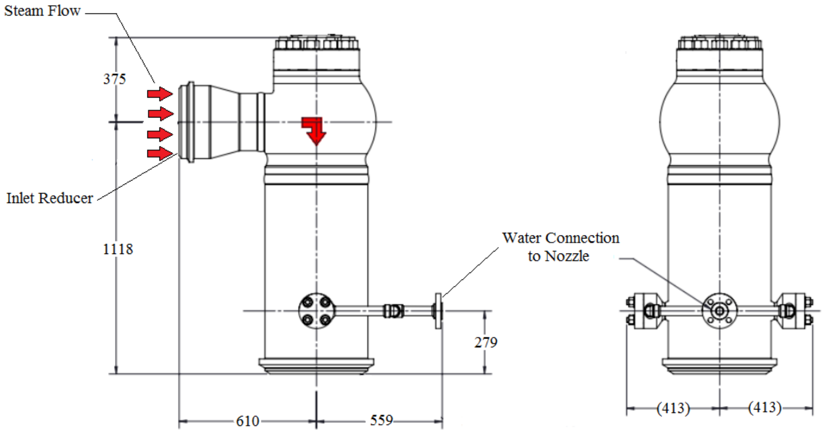


Figure 5: Simulation Setting of Steam Conditioning Valve

Table 3: High Pressure Steam (HPS) Specification

Label	Pressure	Temperature
Valve	50 Bar (5,000,000 Pa)	430ºC
Nozzle	48 Bar (4,800,000 Pa)	280ºC

Table 4: Medium Pressure Steam (MPS) Specification

Label	Pressure	Temperature
Valve	30 Bar (3,000,000 Pa)	430ºC
Nozzle	25 Bar (2,500,000 Pa)	108ºC

Data analysis such as temperature and pressure distribution across the body surface of the steam conditioning valve was carried out. The flow analysis can also pinpoint the critical area of the valve to make the analysis of the thermal stress on the surface easier. From this flow simulation, detailed temperature was extracted specifically from the areas which are experiencing the highest thermal and mechanical loads. Thermal analysis on the surface of the highlighted area of the valve's body surface is important to achieve the objective of this study. The thermal examination of the valve's surface in the specified areas is crucial for understanding how variations in operating conditions lead to the formation of stress concentration over time.

3.0 RESULTS AND DISCUSSION

The Computational Fluid Dynamics (CFD) was simulated in this study for various conditions such as different steam pressure and nozzle condition. Fig. 6 illustrates the spatial distribution of turbulent kinetic energy (TKE) during steam flow through a steam conditioning valve (SCV), highlighting regions of intense turbulence generated by flow acceleration, restriction, and interaction with valve geometry. Recent studies have highlighted that maximum turbulence and heat transfer rates are closely linked to jet interaction and mixing near the nozzle exit, reinforcing the role of turbulence in enhancing thermal and flow processes [9].

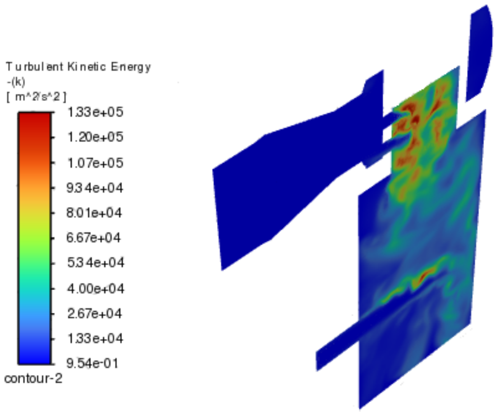
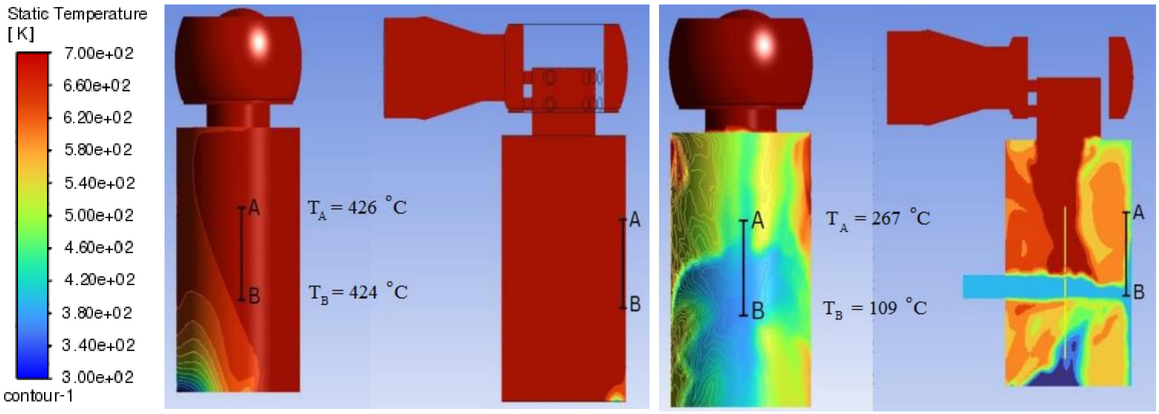


Figure 6: Distribution of Turbulent Kinetic Energy During Steam Flow in Steam Conditioning Valve.

3.1 High Pressure Steam Condition (HPS)

The temperature distribution analysis under High Pressure Steam (HPS) conditions before and after the application of the nozzle is shown in Fig. 5(a) and (b), respectively. Points A and B are two distinct focused points on the wall across from the nozzle inlet which were the subject of the analysis. Point A is where the cracking was found during the inspection as stated in the problem statement, and Point B represents a comparative location that corresponds to the other nozzle. Prior to the application of the nozzle, the temperature distribution along the valve was 427ºC at point A and 424ºC at point B, with a slight loss of about 3ºC due to normal heat transmission and thermal energy conversion and dissipation as illustrated in Fig. 6. This indicates that the flow behaviour along the valve is smooth with no external or internal disturbance. After the nozzle was applied, the temperature at point A and point B dropped drastically to 267ºC and 109ºC. The presence of the nozzle changes the flow characteristics by accelerating the fluid and inducing a rapid pressure drop. Different regions of the valve wall are now exposed to significantly different temperatures that cause non-uniform thermal expansion and contraction. Each cycle of temperature fluctuation causes the material to expand and contract. Over time, this cyclic thermal loading can cause stress and weaken the wall structure. This will initiate microcracks within the valve wall that will lead to risk of structure failure and leakage.

The thermal analysis shows a non-uniform temperature distribution, with a significant temperature drop observed across the nozzle region. This behaviour is mainly attributed to the rapid expansion of high-pressure steam, which induces cooling due to energy conversion from internal energy to kinetic energy during compressible flow. Recent studies have proven that maximum heat transfer and temperature variation occur near the nozzle exit, where expansion and mixing are most intense [9]. Additionally, conjugate heat transfer between solid and fluid domains plays a critical role in shaping the thermal field, as demonstrated in CFD-based thermal systems where strong coupling between wall conduction and fluid flow governs temperature gradients [10]. According to Galic et al., one of the several causes of piping damage even in the absence of applied mechanical loads is the cyclic thermal stresses and strain from temperature fluctuations, degradation, and limitations. Over time, these forces cause the material to expand and compress, creating surface fractures [1]. Any area in a metallic component where relative movement or differential expansion is limited during repeated thermal cycling, the outcome of cyclic pressures brought on by temperature fluctuations adds to damage in the form of cracking [7]. Both claims firmly concur that repeated expansion and contraction of the structure brought on by temperature variations at the wall structure will result in stress and thermal fatigue. Additionally, it was mentioned that if the temperature at the structure swings is higher than 110ºC, cracking may be suspected. This value will indicate the limit before the valve's body starts to crack. Based on the findings, the temperature at Point A and Point B swing at 160ºC and 315ºC. This value exceeds the limit of the temperature swings which will indicate the risk of cracking on the wall's structure.



(a) (b)

Figure 5: Temperature Distribution of HPS (a) Before Nozzle Applied, and (b) After Nozzle Applied

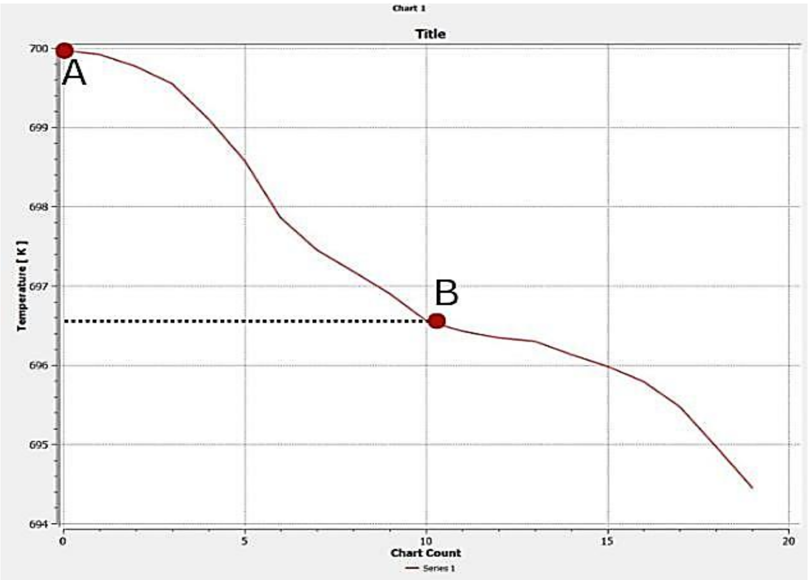


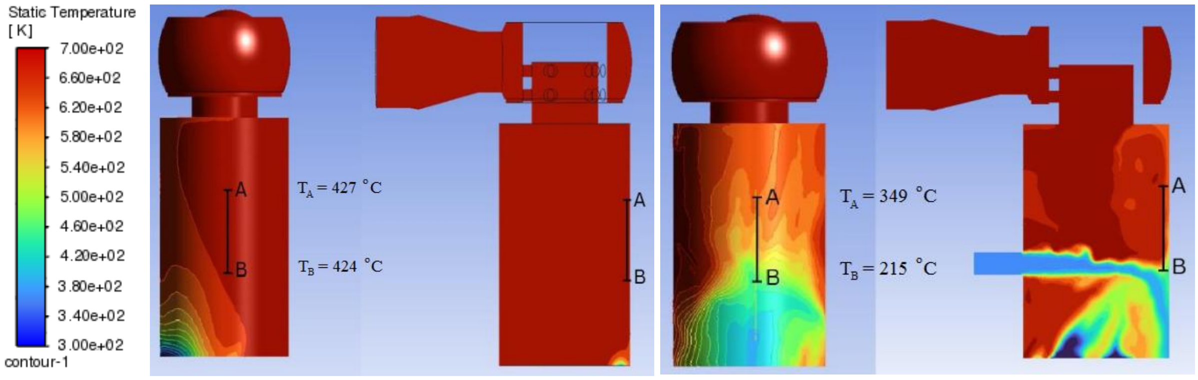
Figure 6: Graph of HPS Temperature Distribution

3.2 Medium Pressure Steam Condition (MPS)

The temperature distribution analysis of the steam conditioning valve was continued by comparing the High-Pressure Steam's scenario with the Medium Pressure Steam condition. This analysis was also conducted at the two focused points of Point A and Point B on the same valve's material and design. Before the nozzle was applied, the temperature distribution along the valve of point A is 427ºC and point B is 424 ºC, with a minor loss around 3 ºC which is total reduction of the temperature as shown in Fig. 7(a). After the nozzle was on, the temperature at point A and point B dropped but slightly higher which is 349ºC and 215ºC as shown in Fig. 7(b). The presence of the nozzle changes the flow characteristics by accelerating the fluid and inducing a rapid pressure drop as shown in Fig. 8.

The temperature swings at Point A and Point B were 78ºC and 209ºC. The temperature swing on point A is lower than 110ºC which is the limit of allowable temperature swings before the structure's material begins to weaken and crack. However, the temperature swings at point B still exceeds 110ºC due to pressure from nozzle inlet. The presence of turbulence further enhances convective heat transfer, resulting in localized cooling and heating zones. These findings are consistent with modern CFD analyses, where forced convection and turbulent mixing significantly influence thermal distribution patterns in high-temperature systems [11, 12]. Temperature range and high-temperature hold time are the main drivers of accelerated crack growth. Mean temperature has a weaker effect on life reduction and thermal stress primarily exhibits transgranular fracture driven by cyclic loading, while creep-thermal fatigue exhibits intergranular fracture caused by the combined action of creep, fatigue, and oxidation which according to an experiment uses specially designed thin-walled tubular specimens with conical holes [8].

The study presented the root cause of the cracking event at the valve middle body wall and nozzle inlet's weldment. The temperature distribution throughout the valve wall was comparatively consistent, indicating stable and undisturbed flow in the absence of the nozzle's inlet, according to the thermal behaviour of the valve under high-pressure steam. However, as soon as the nozzle was turned on, there was a noticeable drop in temperature at both Points A and B, with temperature variations well beyond the critical level of 110ºC for the start of thermal stress. These extreme temperature gradients resulted in non-uniform thermal expansion and contraction, creating cyclic thermal stresses that strongly related with the cracking event that happened at Point A and Point B. The findings confirm that nozzle-induced flow acceleration and pressure drop play a critical role in initiating thermal stress damage within the valve body.



(b) (b)

Figure 7: Temperature Distribution of MPS (a) Before Nozzle Applied, and (b) After Nozzle Applied

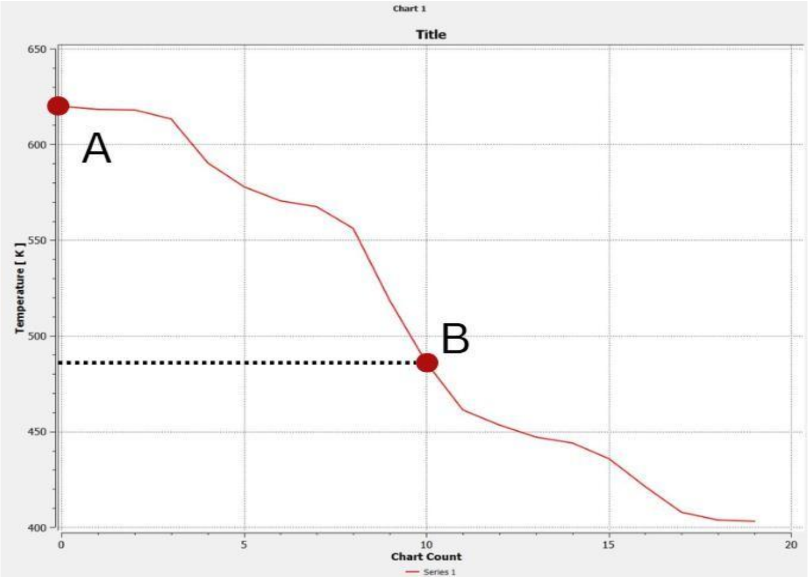


Figure 8: Graph of MPS Temperature Distribution

In order to observe the flow behaviour in the valve under MPS, the pressure at the nozzle input was lowered by comparing HPS and MPS circumstances. When compared to high-pressure situations, the total temperature fluctuations were far smaller. The temperature swing at Point A stayed below the critical limit, indicating a reduced danger of thermal stress. However, Point B continued to experience temperature fluctuations exceeding the allowable threshold, indicating that localized thermal stress remains a concern even at lower operating pressures. This comparison shows that the risk of thermal stress on the structure of the valve is significantly influenced by operating pressure. The implication of the cracking issue may be lessened but not completely resolved under medium-pressure steam circumstances. These findings are in line with current research on compressible flow which demonstrates that the increment of inlet pressure increases temperature gradients, turbulence, and flow acceleration in nozzle systems. In contrast, medium pressure steam exhibits more stable flow characteristics with reduced gradients and lower structural loading, making it more favorable for long-term operation [11, 14].

4.0 CONCLUSION

The overall temperature difference was significantly lower for MPS which is only 38% reduction compared with under HPS conditions which is 59%. The impact of the flow temperature in Steam Conditioning Valve contributes to the cracking event of valve body due to rapid cooling and heat localisation. By comparing high-pressure and medium-pressure steam conditions, the nozzle inlet's pressure was reduced to observe the flow behaviour of valve under Medium Pressure Steam. The overall temperature swings were significantly lower compared with under high pressure conditions.

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AUTHORS CONTRIBUTION

Helmisyah Ahmad Jalaludin: Investigation, Methodology, Secondary analysis, Validation, Writing-Review & Editing.
Muhammad Luqman Muhamad Sharifuddin: Formal analysis, Investigation, Methodology, Writing-Original Draft.
Mohamad Ridzuan Mohamed Rashid: Supervision, Methodology, Validation, Editing, & Writing-Review
Mohamad Zamin Mohamad Jusoh: Methodology, Validation & Writing-Review.

DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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