The Effect of Bend with Sliced Models on the Behavior of Primary Pipe Structures

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**Abstract.** Energy independence is a national goal that requires an equitable energy supply and clean water resources for energy development. A vital aspect of this is efficient clean water transmission to communities, which depends on pipeline network innovation for optimal fluid transport with minimal resistance. Pipeline bends impact stress distribution along pipe walls, where external pressure at bends tends to be higher, necessitating consideration of bending stress in pipe design. Sharp bends can lead to local pressure drops, potentially causing cavitation and pipe wall damage, while sudden flow changes may result in water hammer effects in high-pressure systems. Flow through bends also causes turbulence, erosion, and axial stress, which can be mitigated by expansion joints or flexible couplings. Larger bends impact flow distribution, leading to stagnation zones that can reduce system efficiency. These bends are critical for inspection and maintenance, as they are prone to debris accumulation, corrosion, and wear. Analysis suggests that joint and bend strength should account for the dominant pressure before the turn due to pressure loss after the bend. For instance, the data results indicates that at 729.41 kg/cm² before the turn, pressure decreases to 522.86 kg/cm² after the bend, confirming the necessity of pre-turn pressure as a design consideration.

**Keywords**: Stress, water-pressure, turbulence, cavitation.

# INTRODUCTION

To enhance energy independence, one of the key aspects is the availability of clean water required by the community. To ensure the availability of clean water, a network or transmission system is needed for the distribution of clean water to the public, which functions to transport water from sources to the areas in need. It is crucial to innovate pipe designs that provide optimal and effective fluid distribution. The importance of development and innovation in pipe bend design emphasizes that the chosen model should be effective, efficient, and easy to implement [1, 2].

With government programs related to the availability of clean water, higher education institutions are required to contribute through research and development that supports sustainable energy utilization. In an effort to support energy independence regarding clean water availability, this study discusses the resilience of fundamental transmission pipe elements, particularly at pipe bends [3]. This needs a more in-depth study because although Indonesia has abundant water sources, some regions suffer from a lack of clean water. Both river potential as raw water sources and other water sources are relevant [4, 5].

Transmission pipe networks are one of the means to distribute clean water to areas in need [6]. Among its components are primary distribution pipes, which consist of straight pipes and bend pipes according to the conditions of the route used. As a crucial component in distributing clean water, the design of pipe bends must function optimally as a fluid conductor, with minimal resistance to fluid flow and effective in its implementation. The fluid flow should be efficient and measurable, and the chosen pipe design should be efficient and effective for the fluid flow pressure [7].

In transmission/distribution pipes with wedge model bends, the flowing current will be corrected due to the resistance present on the conduit walls, the angle of direction change, and the size of the bend angle [8]. As the number of wedges increases, the resistance and turbulence affecting the pipe bend decrease. Conversely, with fewer wedges, the resistance increases and the turbulence affecting the pipe walls also becomes greater. This study discusses the impact and flow behavior passing through wedge model bends on the structure of the wedge model pipe bends [9].

Although the magnitude of pressure occurring at bends is primarily influenced by the height difference, the behavior of the flow, such as vortices and erosion caused by the formed flow, requires in-depth study. Changes in pressure and turbulence occurring in the pipe bend with the wedge model will affect the pipe wall structure. Furthermore, with the innovation of the wedge model, each wedge's downstream section will create vortices, and as the number of wedges increases, the vortices appearing downstream will diminish or even disappear [10].

Based on previous research, the stability of pipe walls due to the effects of flow and pressure turbulence, as well as erosion and deposition on pipe bend walls, impacts the internal stress and strain. Dynamic constraints in turbulent pipe flow highlight the impact of wall layer depth on velocity profiles [11]. Additionally, the influence of internal and external pressure, compressive forces, and fluid flow on pipe deformation and instability [12]. The role of free flow turbulence in affecting flow stability through cylindrical elements shows how disturbances can lead to transitions to turbulence [13].

Understanding the dynamics of internal stress and strain in pipes experiencing complex flow conditions and structural changes. The hydraulic effects on the structure of a pipe bend with a wedge model. A wedge model pipe bend is designed flexibly to accommodate conditions in areas of the pipeline network that curve. The study of hydraulic adjustment for wedge model rotating pipe structures focuses on analyzing the impact of different turning radii on flow characteristics and erosion rates [14].

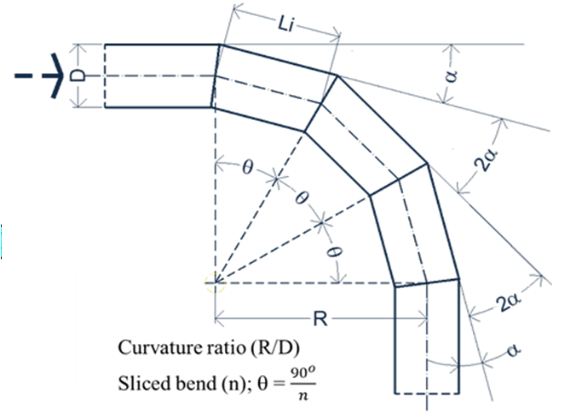
Experimental studies on flexible pipes reveal the impact of internal water pressure and defect length on twist angles, aiding in understanding behavior under various conditions [15]. Additionally, innovative hydraulic systems such as hydraulic wedge systems with adjustable return times offer advantages like longer lifespan, angular flexibility, and quiet operation, demonstrating the benefits of hydraulic solutions in structural applications.

# METHODS

The process and stages of this study begin with preliminary studies, hypotheses, and continue through to the conclusion of the study. Generally, based on the materials reviewed, the assessment of pipes under hydrostatic pressure is based on the strength and durability of the pipes against pressure. In practice, the pressure of the fluid flowing through the pipes or other factors due to activities during installation are considered. For testing PVC, PE, and HDPE pipe materials, laboratory tests are generally conducted using Hydrostatic Pressure and Burst Tester, following applicable standard procedures and guidelines [16].

Tests on steel pipes and similar materials, whether straight or bent pipes, use RSNI 3. 39: 2024 and other standards related to piping work [17-19]. This research focuses more on the study of pipe strength and durability against pressure, particularly the pressure of flowing fluids. The analysis and study are conducted in relation to fluid pressure simulations that impact the structure, adhering to standards and requirements, and accurately representing the actual system conditions.

The model and study completeness are chosen based on the variables to be observed and refer to previous studies [20]. This includes the completeness of flow simulation, pressure propulsion tools, calibrated flow measurement devices, and tools for measuring flow within the pipe [21]. The effect of pressure on the durability and flexibility of the pipe is an important item in the testing, and it represents a manifestation of the fluid pressure that flows through the pipe [17, 20]. The object of study is the pipe bend with a section model as shown in **FIGURE 1** below.



**FIGURE 1**. Geometry of the 90° bend with a slice model

Stress in a pipe due to fluid flow includes longitudinal, radial, and circumferential stress (hoop stress). Longitudinal stress is divided into axial stress and internal pressure. Axial stress ) is caused by axial forces on the pipe. With the axial force () in Newtons, the surface area of the pipe (), flow pressure () in Pascals, the inner cross-sectional area of the pipe () in square meters, the outer diameter of the pipe () and the inner diameter of the pipe () in meters, shown in Eq. 1.

= = (1)

Stress due to internal pressure in a pipe ) is the stress caused by the pressure of the flowing fluid on the pipe's wall. With the flow pressure () in Pascals, the inner radius of the pipe () and the pipe thickness (t) in meters, it is given by Eq. 2.

= (2)

Radial stress is the stress acting in the radial direction or the pipe's radius. The magnitude of this stress varies from the inner surface of the pipe to the outer surface of the pipe. It is positive in the case of vacuum pressure and negative when fluid flow is under pressure. The radial stress of the pipe ) with flow pressure () in Pascals, the outer radius of the pipe (), the inner radius of the pipe (), and the pipe's radius under consideration (r) in meters, is given by Eq. 3.

= - (3)

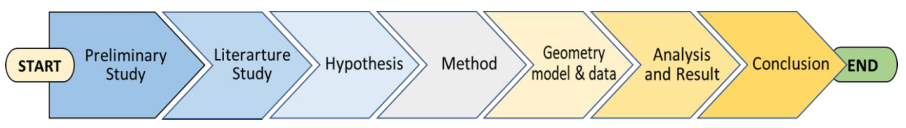
Circumferential stress or hoop stress in a pipe is caused by stress that tends to split the pipe into two parts and is always positive. The pressure acts tangentially, with varying magnitudes, and the pressure experienced by the pipe wall is equal to the fluid pressure. With the flow pressure () in Pascals, the pipe radius (r) and pipe thickness (t) in meters, the equation by Eq. 4.

= (4)

The pressure values at the slice model bend are influenced by the flow velocity (U) and the water surface height (H) under review, shown in Eq. 5.

= ρ . = ρ g H (5)

The subject of this study is based on previous research conducted by the author related to pipe bends with wedge models. [1, 2, 10] . The steps of this study are thoroughly outlined in FIGURE 2. The stages of the study include: preparation of the research; setting up the simulation model according to the specifications; performing flow rate simulations; preparing analysis procedures related to the simulations and other supporting facilities.



**FIGURE 2**. Flowchart of study

This simulation and analysis are related to the impact of flow on the reliability of the pipe structure and joints at bends. The study objects and associated devices include flow measurement systems or measuring buildings as needed for the simulation. The results of this analysis are expected to provide optimal recommendations for the design of joints at bends in the wedge model pipe used.

# RESULTS AND DISCUSSION

Bends in large-diameter pipe distribution networks require specific planning to ensure optimal performance and minimize issues such as pressure loss, excessive stress, and phenomena like cavitation or water hammer. Accurate hydraulic and structural analysis, along with the use of appropriate joints and materials, are crucial for ensuring the reliability and durability of the pipe system. Pipe networks require joints and bends, but these cause greater pressure losses compared to straight pipes. Pressure loss at bends increases turbulence and friction due to the change in flow direction.

Bends cause changes in the distribution of stresses in the pipe wall. The pressure on the outside of the bend is higher than on the inside, resulting in bending stresses that must be considered in the pipe design. Additionally, bends also affect axial stress (along the pipe axis) and hoop stress (circumferential stress). These stresses can lead to deformation if not properly accounted for, especially in large-diameter pipes. Initial conditions to consider include the bend model and the optimal pressure loss resulting from the slice model bend [2], next, the pressures to be calculated are as shown in **TABLE 1** below.

**TABLE 1.** Fluid pressure distribution in a pipe using a slice model bend with an angle up to 90°, based on a physical model with a pipe diameter (di) of 26 mm and a flow velocity (U) of 2.134512 m/s.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No | (n) |  | Slices Number (n) | Geometry for design | | | | | | Pressure drop | | | | Pa (kg/m) | | |
| n |  |  | Li (m) | R/D | f | a |  | U(m/s) | Cpd | Before | Lost | after |
| 1 | 0.7647 | 15 | n=6 | 1 | 15 | 7.5 | 0.02036 | 3.0 | 0.0003 | 0.00023 | 0.02 | 2.13451 | 0.013 | 2,278.07 | 30.09 | 2,247.98 |
| 2 | 0.7647 | 30 | 2 | 15 | 7.5 | 0.02036 | 3.0 | 0.0003 | 0.00047 | 0.05 | 2.13451 | 0.039 | 2,278.07 | 88.85 | 2,189.23 |
| 3 | 0.7647 | 45 | 3 | 15 | 7.5 | 0.02036 | 3.0 | 0.0003 | 0.0007 | 0.8 | 2.13451 | 0.064 | 2,278.07 | 145.61 | 2,132.46 |
| 4 | 0.7647 | 60 | 4 | 15 | 7.5 | 0.02036 | 3.0 | 0.0003 | 0.00094 | 0.11 | 2.13451 | 0.088 | 2,278.07 | 200.46 | 2,077.61 |
| 5 | 0.7647 | 75 | 5 | 15 | 7.5 | 0.02036 | 3.0 | 0.0003 | 0.00117 | 0.14 | 2.13451 | 0.111 | 2,278.07 | 253.45 | 2,024.62 |
| 6 | 0.7647 | 90 | 6 | 15 | 7.5 | 0.02036 | 3.0 | 0.0003 | 0.00141 | 0.17 | 2.13451 | 0.134 | 2,278.07 | 304.66 | 1,973.41 |
| 1 | 0.8071 | 18 | n=5 | 1 | 18 | 9 | 0.0244 | 3.0 | 0.0003 | 0.00028 | 0.02 | 2.13451 | 0.20 | 2,278.07 | 45.51 | 2,232.56 |
| 2 | 0.8071 | 36 | 2 | 18 | 9 | 0.0244 | 3.0 | 0.0003 | 0.00056 | 0.07 | 2.13451 | 0.059 | 2,278.07 | 133.82 | 2,144.25 |
| 3 | 0.8071 | 54 | 3 | 18 | 9 | 0.0244 | 3.0 | 0.0003 | 0.00084 | 0.12 | 2.13451 | 0.096 | 2,278.07 | 217.82 | 2,060.25 |
| 4 | 0.8071 | 72 | 4 | 18 | 9 | 0.0244 | 3.0 | 0.0003 | 0.00113 | 0.16 | 2.13451 | 0.131 | 2,278.07 | 297.75 | 1,980.32 |
| 5 | 0.8071 | 90 | 5 | 18 | 9 | 0.0244 | 3.0 | 0.0003 | 0.00141 | 0.2 | 2.13451 | 0.164 | 2,278.07 | 373.78 | 1,904.29 |
| 1 | 0.8622 | 22.5 | n=4 | 1 | 22.5 | 11.25 | 0.03043 | 3.0 | 0.0003 | 0.00035 | 0.04 | 2.13451 | 0.033 | 2,278.07 | 75.45 | 2,202.62 |
| 2 | 0.8622 | 45 | 2 | 22.5 | 11.25 | 0.03043 | 3.0 | 0.0003 | 0.0007 | 0.11 | 2.13451 | 0.097 | 2,278.07 | 219.96 | 2,058.11 |
| 3 | 0.8622 | 67.5 | 3 | 22.5 | 11.25 | 0.03043 | 3.0 | 0.0003 | 0.00105 | 0.18 | 2.13451 | 0.155 | 2,278.07 | 353.52 | 1,924.55 |
| 4 | 0.8622 | 90 | 4 | 22.5 | 11.25 | 0.03043 | 3.0 | 0.0003 | 0.00140 | 0.24 | 2.13451 | 0.209 | 2,278.07 | 476.97 | 1,801.1 |
| 1 | 0.9388 | 30 | n=3 | 1 | 30 | 15 | 0.04038 | 3.0 | 0.0003 | 0.00047 | 0.07 | 2.13451 | 0.063 | 2,278.07 | 144.26 | 2,133.81 |
| 2 | 0.9388 | 60 | 2 | 30 | 15 | 0.04038 | 3.0 | 0.0003 | 0.00093 | 0.19 | 2.13451 | 0.181 | 2,278.07 | 412.59 | 1,865.48 |
| 3 | 0.9388 | 90 | 3 | 30 | 15 | 0.04038 | 3.0 | 0.0003 | 0.00140 | 0.3 | 2.13451 | 0.283 | 2,278.07 | 645.1 | 1,632.97 |
| 1 | 1.0585 | 45 | n=2 | 1 | 45 | 22.5 | 0.0597 | 3.0 | 0.0003 | 0.00069 | 0.15 | 2.13451 | 0.156 | 2,278.07 | 354.79 | 1,923.28 |
| 2 | 1.0585 | 90 | 2 | 45 | 22,5 | 0.0597 | 3.0 | 0.0003 | 0.00138 | 0.4 | 2.13451 | 0.421 | 2,278.07 | 959.29 | 1,318.78 |
| 1 | 1.2996 | 90 | n=1 | 1 | 90 | 45 | 0.11031 | 3.0 | 0.0003 | 0.00127 | 0.5 | 2.13451 | 0.651 | 2,278.07 | 1,484.06 | 794.01 |

Source: Analysis result

Referring to previous studies, the optimum performance for a slice model bend has a value of R/D = 3, with a bend angle of up to 90°, and the number of slices (n) ranging from 1, 2, 3, 4, 5, 6. The pressure drop coefficient is () = ϖ (δa+δb), where "before" is the pressure before the bend, "after" is the pressure after the bend, and "lost" represents the amount of pressure lost due to the slice model bend. The friction coefficient (f) is based on the Moody diagram and can also be determined using a tria-error method.

In high-velocity fluid flow, sharp bends can cause a significant local pressure drop, which may lead to cavitation. This results in the formation of vapor bubbles and can damage the pipe walls due to erosion effects when the bubbles collapse. Sudden changes in flow direction caused by pipe bends can also result in flow reversal (water hammer) in high-pressure piping systems. Flow reversal occurs when a pressure wave in the fluid flow abruptly stops or changes direction. The following are the results of the analysis produced from the model used in this study.

**TABLE 2.** Pressure acting before and after a 90° bend model  
due to flow velocity (U) 2.134512 m/s

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No. | () | Pressure drop | | | | | Pa (kg/cm) | | |
| [n] | [R/D] | do (cm) | di (cm) | Cpd | Before | lost | after |
| 1 | 90o | 6 | 3 | 2.7 | 2.6 | 0.134 | 22.78 | 3.05 | 19.73 |
| 2 | 90o | 5 | 3 | 2.7 | 2.6 | 0.164 | 22.78 | 3.74 | 19.04 |
| 3 | 90o | 4 | 3 | 2.7 | 2.6 | 0.209 | 22.78 | 4.77 | 18.01 |
| 4 | 90o | 3 | 3 | 2.7 | 2.6 | 0.209 | 22.78 | 4.77 | 16.33 |
| 5 | 90o | 2 | 3 | 2.7 | 2.6 | 0.283 | 22.78 | 6.45 | 13.19 |
| 6 | 90o | 1 | 3 | 2.7 | 2.6 | 0.651 | 22.78 | 14.84 | 7.94 |

Source: Analysis result

Based on **TABLE 2** above, it shows the pressure acting on the study model of a pressurized pipe with a diameter of 26 mm and segmented bend models varying with a flow velocity of 2.134512 m/s. The pressure acting on different segmented bend models studied shows that the pressure on the upstream side of the bend tends to be similar because it is at the beginning of the flow. In contrast, the pressure on the downstream side of the bend varies according to the magnitude of the resistance coefficient caused by the segmented bend model.

**TABLE 3.** Stresses acting on the walls of a 90° segmented bend pipe model with a diameter of 26 mm  
due to a flow velocity (U) of 2.134512 m/s

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No. |  | |  | |  | |  | |  | |
| before | after | before | after | before | after | before | after | before | after |
| 1 | 290.56 | 251.7 | 148.07 | 128.27 | -11.07 | -9.59 | 301.84 | 261.48 | 729.41 | 631.86 |
| 2 | 290.56 | 242.89 | 148.07 | 123.78 | -11.07 | -9.25 | 301.84 | 252.32 | 729.41 | 609.73 |
| 3 | 290.56 | 229.73 | 148.07 | 117.07 | -11.07 | -8.75 | 301.84 | 238.65 | 729.41 | 576.69 |
| 4 | 290.56 | 208.28 | 148.07 | 106.14 | -11.07 | -7.93 | 301.84 | 216.37 | 729.41 | 522.86 |
| 5 | 290.56 | 168.21 | 148.07 | 85.72 | -11.07 | -6.41 | 301.84 | 174.74 | 729.41 | 422.26 |
| 6 | 290.56 | 101.27 | 148.07 | 51.61 | -11.07 | -3.86 | 301.84 | 105.21 | 729.41 | 254.23 |

Source: Analysis result

By examining various aspects that occur at a bend in a pipeline network, the flow phenomenon varies greatly with the free behavior depending on the conditions present at the pipe bend. In this study, the analysis is conducted on various conditions, including axial stress, internal stress, radial stress, and shear stress occurring at a 90° segmented bend. This study focuses on a pressurized pipe model with an inner diameter (di) of 26 mm and an outer diameter (do) of 27 mm.

These stresses occur due to the increasing pressure and flow velocity, as well as the presence of bends. The smaller the bend radius, the greater the stress at the bend. For certain fluids, if the viscosity of the flowing fluid increases, the resulting stress also becomes higher. The type of material and the roughness of the pipe wall, which impede flow, also contribute to pipe stress, as does the material's elasticity and tensile strength.

|  |  |
| --- | --- |
| (a) | (b) |

**FIGURE 3.** Flow behavior in a 90° pipe bend model (a) cross-sectional profile with a slice (n) of 1; (b) flow behavior in a sliced bend model with a slices (n) from 1 to 3.

Based on **FIGURE 3**, the flow profile in the 90° sliced bend model is clearly visible. In (a) cross 1 and cross 6, it illustrates the flow in a straight path uniformly distributed around the pipe wall with high pressure, leading to significant axial stress at the center, which gradually decreases toward the edges. In (a) cross 2 and cross 4, turbulence is evident on the inner side of the bend due to the sliced bend model, causing back pressure. Similarly, in cross 3, erosion occurs on the outer side of the bend. In (a) cross 5, vortexes are still present on the downstream side due to the turbulence from the sliced bend model.

In **FIGURE 3**. (b), it is clearly illustrated that the flow behavior in a sliced bend model shows that as the number of slices increases, turbulence, erosion, and axial stress will decrease as the resistance decreases due to the bend becoming smoother and the model of the bend becoming more gradual. Therefore, the stress changes occurring at a bend significantly affect the bend itself, making the optimal welding thickness and model crucial to ensure the joint's safety during operation.

The selection of the appropriate fitting, such as bends (45° or 90°) or tees, is very important. For large-diameter pipes, long-radius bends are usually chosen to reduce pressure loss and avoid damage due to excessive stress, although excessively long bends may have the opposite effect. Expansion joints or flexible couplings can be used to accommodate pipe movement and reduce stress caused by bends, especially in large-diameter pipes.

Bends in large pipes can affect flow distribution within the system, causing uneven flow or the formation of stagnation zones, which can reduce the efficiency of the distribution system. Bends also become critical points for inspection and maintenance, as they often collect debris or particles carried by the flow and are also vulnerable to corrosion or wear. In the bend of the slice model, this condition will become more extreme than the state in the smooth pipes as seen in previous studies. The resistance to flow turbulence is very high because the bends in the slice model at the joints of the slices are rougher, and the fewer the number of slices, the rougher it becomes due to the increased turbulence. Therefore, in such conditions, the turns in the slice model must be stronger compared to curved bends.

# CONCLUSIONS

A bend causes a change in stress distribution on the pipe wall. The pressure on the outer side of the bend tends to be higher, causing bending stress that must be considered in pipe design. In high-velocity fluid flow, sharp bends can lead to significant local pressure drops, which may cause cavitation. This results in vapor bubbles that can damage the pipe walls. Sudden changes in flow direction due to bends can cause backflow (water hammer) in high-pressure piping systems. This occurs because both pressure and flow velocity increase at the bend, and the smaller the bend radius, the greater the stress. The flow behavior in a slice-model bend shows that with more slices, turbulence, erosion, and axial stress increase but gradually decrease as resistance decreases with smoother bends.

In large-diameter pipes, long-radius bends are typically chosen to reduce pressure loss and avoid damage from excessive stress; however, overly long bends can have the opposite effect. Expansion joints or flexible couplings can be used to accommodate pipe movement and reduce stress caused by bends, especially in large-diameter pipes. Large pipe bends can affect flow distribution within the system, leading to uneven flow or the formation of stagnation zones, which can reduce the efficiency of the distribution system. Bends also become critical inspection and maintenance points, as they are often where debris or particles carried by the flow accumulate, and are also prone to corrosion or wear. Based on the analysis results, the dominant pressure in considering the strength of the joints and the turns of the slice model can use the pressure that acts before the turn. Because the pressure that acts after the turn will be corrected due to the pressure loss that occurs. For example, with the pressure in **TABLE 3**, number 4, using 3 slices, the pressure before the turn is 729.41 , and the pressure after the turn is 522.86 .

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