Comparative Analysis of Control Structures in Core Annular Flow Systems: A CFD Simulation Study

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Abstract: This paper investigates the application of two distinct control structures, conventional single-layer control and cascade control, in a Core Annular Flow (CAF) system simulated through Computational Fluid Dynamics (CFD). Both control strategies were tested and carried out open-loop tests to tune the controllers following the SIMC rules. Results demonstrate that both structures, one I controller for the oil fraction and one cascade controller PI-I for the velocity ratio and the oil fraction, successfully controlled the system, each exhibiting unique behaviors and performance characteristics. The analysis highlights the strengths and limitations of each approach, where the single-layer structure with an I controller was faster to reach the setpoint and was efficient to reject disturbances.

Keywords: Modeling and Simulation, Multiphase Flow, Computational Fluid Dynamics, Process Control Applications, Nonlinear Process Control

1. INTRODUCTION

The Core Annular Flow CAF pattern is a significant phenomenon in fluid dynamics, particularly in multiphase flow systems. It occurs when a highly viscous fluid, like heavy crude oil, is surrounded by a less viscous fluid that forms an outer annular layer inside pipelines. In many industrial contexts, such as in the oil and gas sector, water is often used as the outer fluid, acting as a lubricant around the viscous oil core. This arrangement is crucial for reducing the friction between the oil and the pipeline walls, which enhances flow efficiency and lowers energy consumption (Tripathi et al. 2017).

As shown in Fig. 1.a and Fig. 1.b, in red, high-viscosity oil at the middle of the flow and in blue water, functioning as a lubricating layer.

Fig. 1.a - Example of Core Annular Flow, side view.

Fig. 1.b - Example of Core Annular Flow, 3D views.

This configuration enhances fluid transport efficiency while lowering pumping expenses and minimizing environmental impact. As illustrated in Fig. 1.a and 1.b, the interface between water and oil during the CAF operation shows a wavy pattern, suggesting that the system is close to instability. This equilibrium implies that any disruption could trigger a regime shift, pushing the process into an unstable and less efficient operational state (Joseph et al. 1997).

The application of CAF in the oil industry has a long history. The concept of water lubrication for transporting oil was first introduced in 1904 by Isaacs and Speed, who suggested stabilizing light oil by using centripetal forces generated through pipe rifling. Later, Clifton and Handley, working for Shell Development, proposed a technique to prevent oil emulsification during pumping by removing water before pumping and reintroducing it into the pipeline afterward (Xie et al., 2023).

CAF has been extensively applied in Venezuela, where a 55-kilometer pipeline was used to transport high-viscosity oil with a viscosity of 1.5 Pa·s. Additionally, Orimulsion, a fuel produced in Venezuela and marketed by Bitor, was also successfully transported using this method. Another notable example is the Shell Development project in California, which constructed a 38 km, 15 cm diameter pipeline to transport heavy crude oil. This pipeline operated for years, moving 24 000 barrels of viscous crude oil per day using water lubrication (Xie et al., 2023).

While widely used in large-scale transport systems, Core Annular Flow faces several critical challenges. These include destabilization of the annular flow due to variations in pipeline geometry or shifts in flow direction, fouling from viscous fluids adhering to the pipeline walls, and the formation of emulsions caused by impurities or water, which can disrupt the stability of the flow pattern (Xie et al., 2023).

Due to buoyancy effects, maintaining CAF stability over long distances is particularly complicated. Overcoming these issues is essential for enhancing CAF's efficiency in various applications. Control mechanisms can address these challenges. Interestingly, while PID controllers are recognized for their stabilizing effects, they have not been widely implemented in CAF systems. The introduction of simpler control structures could offer an effective solution for stabilizing flow.

The concept of using control to stabilize unstable flow regimes has been previously discussed in the literature for other systems. For instance, in addressing the challenge of slugging in multiphase flow systems, Ohrem et al. (2017) developed robust anti-slug control strategies using both linear and nonlinear approaches. Their research demonstrated that PI controllers, when carefully tuned, can effectively stabilize flow in pipeline-riser systems, particularly when using upstream pressure measurements. Additionally, more advanced techniques, such as $\mathscr{L}_1$ adaptive control, were introduced to enhance system stability where traditional PI controllers were less effective. These methods were validated through both simulations and experimental setups, offering a reliable solution for maintaining steady flow in offshore production systems.

To try understanding the problem from a phenomenological point of view Jiang et al. (2014) conducted a CFD simulation study using the VOF method to analyze oil-water core annular flow (CAF) through U-bends. The research explored the influence of fluid properties, pipe geometry, and flow parameters on hydrodynamic performance and fouling behavior. Their findings highlighted the importance of optimizing design and operational conditions to minimize fouling and improve flow stability, making valuable contributions to pipeline transport efficiency in heavy oil applications.

In Wen et al. (2023) the CAF simulations were done using the Volume of Fluid (VOF) method in CFD, a relevant study is one where oil-water CAF was simulated through a 90° elbow pipe. This study used the VOF method, combined with the standard k-ε model, to investigate hydrodynamic performance and stability. It focused on the effects of variables such as inlet water fraction, superficial velocities of oil and water, and oil properties (density and viscosity) on the flow behavior. The results confirmed the applicability of the VOF model to predict the CAF's stability and hydrodynamic characteristics, providing valuable insights for the optimization of pipeline designs

Lima et al. (2023) presented a study on enhancing Core Annular Flow (CAF) stability in heavy oil transport using feedback control strategies. A Proportional-Integral (PI) controller was developed to maintain flow stability and prevent fouling. Using CFD simulations, the study demonstrated that adjusting water flow dynamically can improve system efficiency and manage disturbances, offering a new approach to optimizing CAF operations.

Therefore, the objective of this work is to develop and apply different control structures, a conventional PID controller and a cascade controller, where the ability to reject disturbances and return to the setpoint was tested.

2. CFD MODELLING AND SIMULATION

2.1 Case of study and virtual plant

To carry the CAF the nozzle design is crucial in the system; the nozzle generally features a coaxial design, consisting of two concentric passages, as shown in Fig. 2, where blue represents the water and red represent the oil. The inner passage carries the high-viscosity oil, while the outer passage injects the lower viscosity fluid. This design is key to reducing shear forces at the interface and promoting the formation of a lubricating film around the oil core.

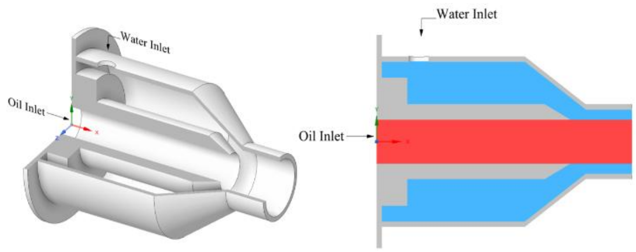

Fig. 2 - Example of Core Annular Flow nozzle.

The development of geometry is a crucial initial step in CFD modelling, where a virtual model of the physical domain is constructed. One simplification of this geometry can be seen in Fig. 3, moreover shows the CAF inlet, consisting of three entry points for the induction head: one 20 mm entry for oil and two 2.5 mm entries for water. The geometry of the modelled CAF unit is also depicted in Fig. 3. The inlet was connected to a pipe, a straight horizontal aluminum structure with a length of 1000 mm.

Fig. 3 – System dimensions.

After developing the geometry, the domain was discretized into smaller units, known as cells or elements, through mesh generation. This grid forms the basis for CFD simulations, as fluid dynamics equations are solved within each cell. The mesh's quality directly impacts the accuracy of the simulation: a finer mesh provides more detailed results but increases computational demands and solution time.

To detail and computational efficiency, targeted mesh refinement was applied in critical areas, such as near walls or where significant flow gradients occur. The mesh setup for this study was determined through a sensitivity analysis to ensure both accuracy and real-time processing capability, which is essential for the control system's operation.

A structured mesh was created with additional refinement near boundaries, resulting in 9,033 elements and 8,515 nodes. The mesh quality was evaluated, achieving an average score of 0.84, indicating a good balance between precision and computational efficiency. Fig. 4 shows the mesh layout, including the refined areas.

Fig. 4 – Mesh of system

Once the geometry is defined and the mesh is generated, the next step is to configure the simulation setup. Interfacial tension, viscosity, and density are key factors in CFD modeling of multiphase flows. Interfacial tension governs the stability and shape of phase boundaries, viscosity affects flow resistance, and density impacts buoyancy and phase distribution, Jiang et al. (2014). These properties are crucial for accurately simulating flow dynamics, the values that were used in the simulation can be seen in Table 1.

Table 1. Physical-chemical properties of system.

	Water	Oil
Specific Mass	999.8 kg/m³	854 kg/m³
Dynamic Viscosity	0.001 Pa s	0.62 Pa s
Interfacial Tension	0.032 N/m	

Using the model with standard k-epsilon turbulence and enhanced wall treatment in multiphase flow simulations offers an effective compromise between accuracy and computational efficiency when capturing turbulence and phase interactions. The Volume of Fluid (VOF) model, applied for this multiphase flow, handles two Eulerian phases, allowing precise tracking of the interface between them. This approach ensures a reliable representation of complex fluid dynamics while keeping the computational demands manageable Wen et al. (2023).

3. OPEN AND CLOSED LOOP RESULTS

In this section, the simulations for control design and performance evaluation will be described. Two main control concepts are considered, see Fig. 5.a and Fig. 5.b. In the first (Fig. 5.a), a simple control structure is proposed for tracking the oil fraction at the pipe outlet by manipulating the water velocity. Where u_w is the water velocity, $u_o$is oil velocity, σ is the oil fraction and σ^{sp} the setpoint of oil fraction.

The second control structure (Fig. 5.b) consists of a cascade strategy, where the oil fraction controller setpoint is manipulated by another controller, which aims to keep the ratio at a reference setpoint, where ε is the ratio and defined according to:

$$\varepsilon = \frac{u_w}{u_o} \tag{1}$$

These control structures will be compared in terms of the system's stability and performance.

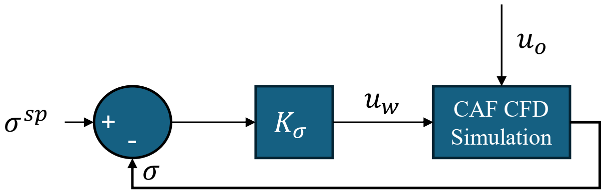

Fig. 5.a – Structure I, PID controller. K_σ represents the controller for oil fraction, σ.

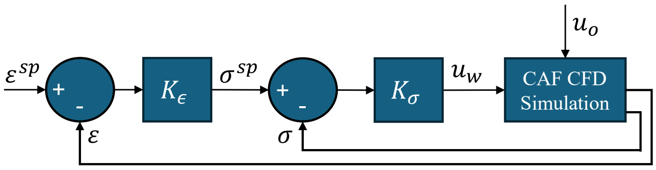

Fig. 5.b – Structure II, Cascade controller

3.1 Disturbance test

Initially, open-loop CFD simulations were performed to analyze the system's response to different disturbance values. Here, the manipulated variable was kept constant, while the oil disturbance was varied over time. This approach allowed for the analysis of how changes in oil flow impact the system's dynamics and overall performance.

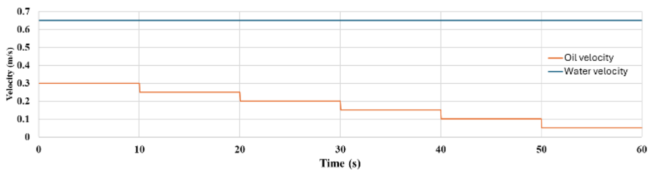

Fig. 6.a – Input values for disturbance test

With this, it is possible to observe the response of the controlled variable in Fig. 6.b, as well as the specific frames from the simulation in Fig. 6.c. These visuals help illustrate how the system reacts to the varying oil disturbance over time.

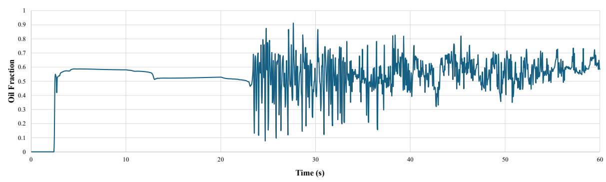

Fig. 6.b – Simulation results for disturbance test

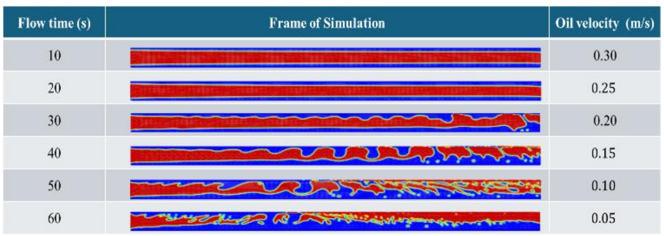

Fig. 6.c – Flow patterns for disturbance test

We can see that disturbances on oil flow heavily influence the flow pattern, and the system cannot cope with such disturbances in an open loop. Therefore, closed-loop operation of this system is deemed necessary for dealing with varying oil flows.

3.2 Step response and tuning for oil fraction controller

As observed in the disturbance test, at a velocity of 0.2 m/s, the disruption of the Core Annular Flow began. Due to this, a constant disturbance value was applied, and a test was conducted with the manipulated variable around this value, Fig. 7. a.

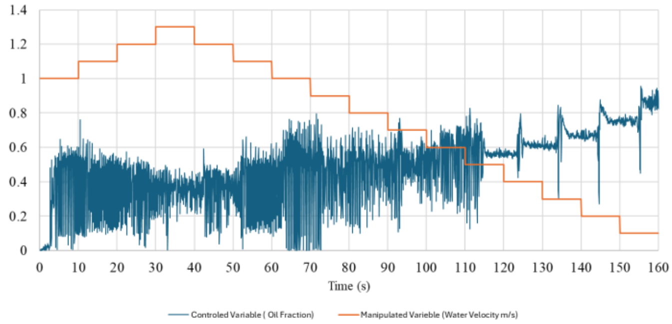

Fig. 7.a – Step response without filter

Afterward, it was observed that the output signal was extremely noisy, making it difficult to apply tuning techniques to this type of signal. To address this issue, a 2-second moving average filter was applied to smoothen the data, resulting in the image shown in Fig. 7.b. This adjustment helped to reduce noise and provided a clearer signal for further analysis and tuning.

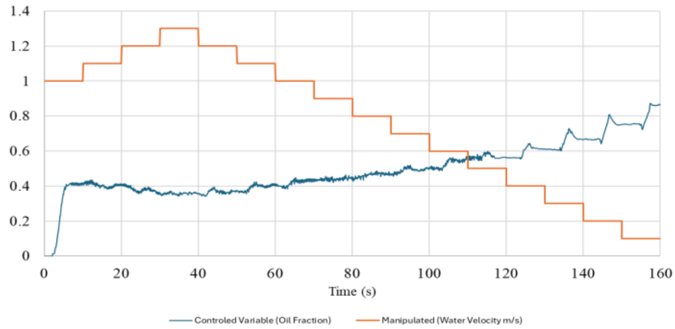

Fig. 7.b – Step response with filter

The results in Fig. 7.b show that the system's behavior is primarily governed by the time delay coming from the fluid transport time in the pipe. Therefore, for control tuning purposes, the system can be approximated as a pure time delay model, meaning that the time constants can be neglected compared to the effective time delay. Given this approximation, the application of the SIMC tuning rules (Skogestad, 2003) results in a pure integral controller, with tuning given by:

$$K_I = \frac{1}{k(\tau_c + \theta)} \tag{2}$$

Here, K_I represents the integral gain of the controller, k is the system gain, τ_c is the desired closed-loop response time, and θ refers to the dead time or delay. As shown in Fig. 7. And 7.b the system exhibits nonlinear behavior, consequently, various values of K_I were calculated for the different expected operating conditions. The tuning parameter was chosen as τ_c = θ = 8 seconds, and the corresponding tunings are detailed in Table 2.

Table 2. Tuning parameters for K_σ.

Description	k	K_I
Low gain	-0.68	-0.090
Mean gain	-0.51	-0.122
High gain	-0.25	-0.245

A lower process gain k represents a lower effect of the manipulated variable on the system output. In this case, the integral gain K_I must be increased. The complete simulation results are displayed in Fig. 8.

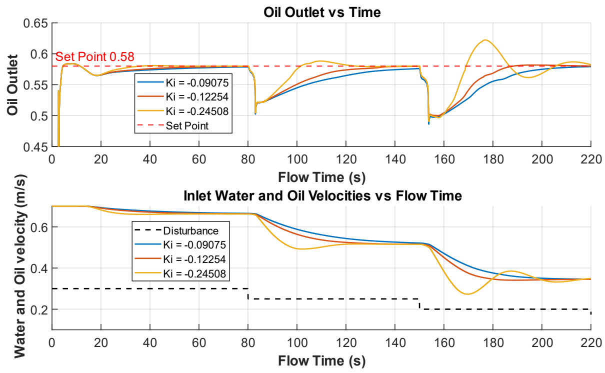

Fig. 8 – Closed loop system

Here, we can see that higher K_I values result in a faster response to disturbances but come at the cost of increased oscillations and instability, which is particularly noticeable in the oil outlet. On the other hand, lower K_I values provide more stability but lead to slower convergence to the setpoint. Depending on the system's priority, whether faster disturbance rejection or smoother stability, the choice of K_I should be adjusted accordingly. In this case, $K_I = 0.12254$ seems to offer a good balance between stability and responsiveness.

3.3 Step response and tuning for ratio controller

As in the first open-loop test conducted for the oil fraction controller, an open-loop test was also performed for the ratio controller, see Fig. 8. Here the tuning chosen for the oil fraction controller (slave) was $K_I = -0.12254$, according to the results presented in the previous subsection.

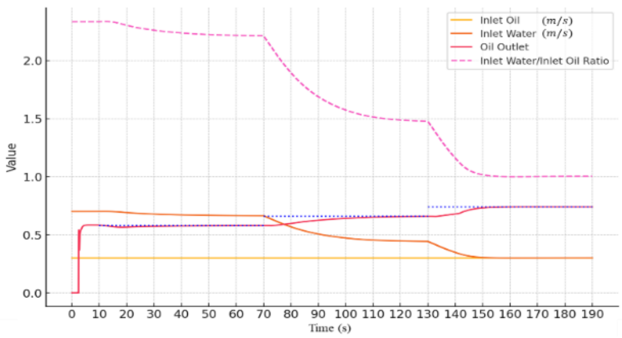

Fig. 8 – Step response struct II

Based on the step response test conducted for the second control structure, it was possible to approximate the system's dynamic characteristics through the identification of first order plus time delay transfer functions. The identified parameters are presented in Table:

	k	τ	θ
Step I	-8.87	-0.090	0
Step II	-6.12	-0.079	0

Using this information, the SIMC tuning method defined by (2)-(4) was applied (Skogestad, 2003), leading to the tuning parameters in Table 3.

$$K_c = \frac{1}{k}\frac{\tau}{(\tau_c + \theta)} \tag{3}$$

$$\tau_I = \min\{\tau\,; 4(\tau_c + \theta)\} \tag{4}$$

$$K_I = \frac{K_c}{\tau_I} \tag{5}$$

	τ_c	k_c	τ_I	K_I
Step I	40	-0.046	16.5	-0.046
Step II	40	-0.037	9.15	-0,037

Table 3. Tunning parameters of struct II

The closed-loop system performance face to setpoint changes and disturbances is shown by the simulation results presented in Fig. 9.a and Fig. 9.b.

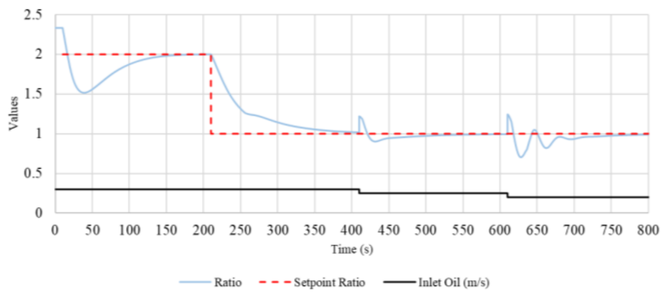

Fig. 9.a – Struct II, closed loop, master control

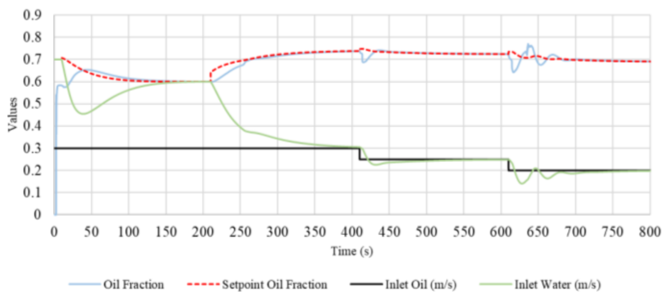

Fig. 9.b – Struct II, closed loop, slave control

After this to comparing the structure both controllers, in the same conditions was taking the value oil fraction that was seen in the Fig.9.b, around 0.7, and another simulation was did for structure I. The results is showed in Fig.10.

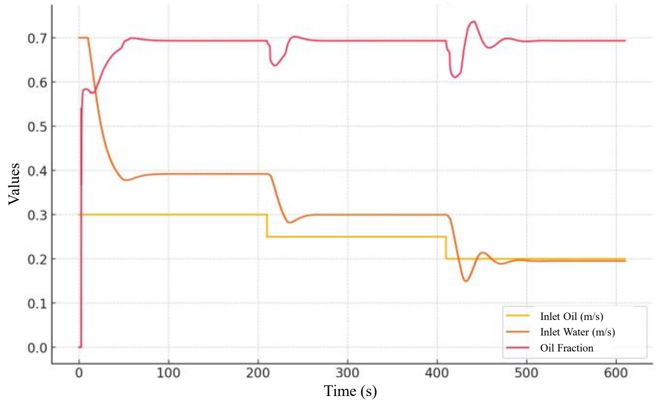

Fig. 10 – Struct I, doing the setpoint founded for struct II

4. DISCUSSION

In this work, we proposed two control structures for the operation of a Core Annular Flow (CAF) system, see Fig. 5. The main objectives for these control structures are preserving the flow pattern under the effect of disturbances and maximizing the system productivity. In this sense, a cascade control structure (Fig. 5.b) is proposed with the goal of dividing the control tasks: the internal control layer is responsible for rejecting the main disturbance of the system, and the external layer tries to increase the fraction of oil in the pipe reducing the water quantity for transport.

Comparing the individual results of the control structures, both were successful in stabilizing the system. However, the two-layer control structure, which uses the ratio between water and oil, exhibited a slower response compared to the single-layer control structure. This is because, in the cascade control approach, the master controller necessarily needs to be slower than the slave controller, impacting the overall system response time.

From the results shown in Fig. 9, we see that the external control layer does not significantly change the steady-state value of the internal control layer when the disturbance value changes. This means that the external layer did not achieve its main goal through feedback alone, and a setpoint change had to be imposed in the system to achieve this goal. Nevertheless, different control structures can be proposed to increase the operational flexibility, enabling stable performance over a wider range of operating conditions.

Initially, the setpoint for the single-layer control structure was defined based on previous experiments and simulations, heuristically, that determined the ideal amount of oil to be maintained in the pipeline. However, when using the control structure based on the water-to-oil ratio, the setpoint for the amount of oil in the system was set by the upper layer, or master controller. In this case, it was observed that the controller increased the setpoint for the amount of oil in the pipeline, resulting in a higher proportion of oil and a reduction in the amount of water needed for transport.

This change brings important benefits to system efficiency, as increasing the amount of oil and consequently reducing the amount of water required for transport decreases resource consumption, especially water, which is used as a lubricant in the flow process. This not only optimizes the transport process but also reduces operational costs and minimizes environmental impact by lowering excessive water usage.

5. CONCLUSION

This study explored the application of two distinct control structures in a Core Annular Flow (CAF) system, aiming to improve the efficiency and stability of heavy oil transportation. Through CFD simulations and response tests, it was possible to analyze in detail the system's behavior under different operational conditions and disturbances. Both control structures, single-layer and cascade control, were able to stabilize the system, each with specific characteristics that suit different scenarios.

The single-layer control structure provided a faster response, based on previous experiments and simulations, ensuring the maintenance of an adequate proportion of oil in the pipeline. However, the cascade control structure, which uses the water-to-oil ratio, while slower due to the hierarchical nature of its controllers, which can in the future be used to expand the system's operational zones. This feature was particularly useful in dynamically adjusting the oil flow setpoint, increasing efficiency by reducing the amount of water used for transportation.

The results reinforce the importance of applying advanced control methods to multiphase systems like CAF, where flow stability is crucial for safe and efficient operation. Moreover, the ability to dynamically adjust the amount of oil in the system provides greater operational flexibility, allowing the system to operate in a wider range of conditions.

Therefore, this work contributes not only to understanding multiphase flow dynamics but also to implementing control solutions that can enhance efficiency and reduce operational costs in heavy oil transportation industries. The adoption of cascade controllers, with the potential to expand operational zones and optimize resource usage, stands out as a promising strategy for addressing the challenges posed by transporting high-viscosity fluids over long distances.

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