XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

# CFD Modeling of Sanitary Effluent Flow in Parshall Flumes Considering Surface Tension Variability

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**Abstract.** This study investigates the behavior of sanitary effluent flow in Parshall flumes using Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent. The central hypothesis is that wastewater surface tension, differing from that of pure water, significantly affects hydraulic behavior—especially in the critical regions of the flume. To represent wastewater, water was used as the base fluid, with surface tension varied across three scenarios (0.030, 0.040, and 0.050 N/m), based on values from literature. The flow was modeled as two-phase (water–air), incompressible, and transient. The Volume of Fluid (VOF) method captured the interface, and turbulence was addressed using the k-ω SST model due to its effectiveness in resolving shear layers. Boundary conditions included uniform inlet velocity, atmospheric outlet pressure, rough no-slip walls, and a free surface. Results showed that lower surface tension increases surface instability, recirculation, and air entrainment—factors that may compromise flow measurement, particularly with ultrasonic or pressure sensors. Velocity fields and stage–discharge curves also varied, with higher tensions producing smoother flows. The study concludes that surface tension is a non-negligible factor in CFD modeling of wastewater in Parshall flumes. It influences not only flow visualization but also internal hydraulic behavior, with implications for accurate flow measurement in sanitary engineering.

**Keywords:** CFD, Parshall flume, surface tension, wastewater flow modeling, turbulence model.

## 1 Introduction

Parshall flumes are hydrometric devices widely used for measuring volumetric flow rates in open channels. Their practical application is especially prominent in water treatment plants (WTPs) and wastewater treatment plants (WWTPs). The popularity of these hydraulic structures is attributed to their simple construction, low maintenance cost, and high accuracy under ideal flow conditions. However, the measurement accuracy can be significantly affected by factors that alter the fluid dynamic behavior of the flow, particularly in critical regions of the flume geometry, such as the throat.

In the case of wastewater, physical and chemical properties—such as surface tension—have gained increasing attention in the scientific literature due to their direct influence on the air–wastewater interface. Consequently, surface tension variability leads to the formation of recirculation zones, aeration, and surface instabilities that directly impact flow measurement and the performance of Parshall flumes.

In this context, the present study aimed to analyze the flow behavior of sanitary effluents in Parshall flumes using Computational Fluid Dynamics (CFD) simulations performed with ANSYS Fluent. The central hypothesis is that the surface tension of wastewater, lower than that of pure water, significantly influences flow stability and the reliability of hydraulic measurements.

To this end, water was adopted as the base fluid, and surface tension values were varied according to literature

recommendations to represent different typical conditions of industrial and domestic wastewater. The modeling was conducted using a two-phase (water–air), incompressible, and transient approach.

The Volume of Fluid (VOF) method was applied to track the interface between phases, and turbulence was modeled using the k-ω SST model, which is well-suited for capturing strong shear gradients and boundary layer effects. The boundary conditions reflected realistic operational scenarios in wastewater channels, including uniform velocity at the inlet, atmospheric pressure at the outlet, rough no-slip walls, and a free surface at the top.

From this perspective, the study contributes to a detailed understanding of the effects of surface tension in numerically simulated sanitary flows, proposing a realistic and computationally efficient approach. The results have relevant practical implications for the calibration of level sensors and the improvement of flow measurement system design and operation in sanitary engineering.

# 2 Theoretical background

## 2.1 Parshall Flumes: design, operation and hydraulic principles

The Parshall flume is a hydraulic device developed by Ralph L. Parshall in 1922, designed to enable flow rate measurement in open channel systems. Geometrically, the flume consists of a sequence of distinct sections: a level approach section, a converging section at the same level, a narrow and downward-sloping throat, a diverging section with an upward slope, and a final outlet section with a drop (Figure 1).

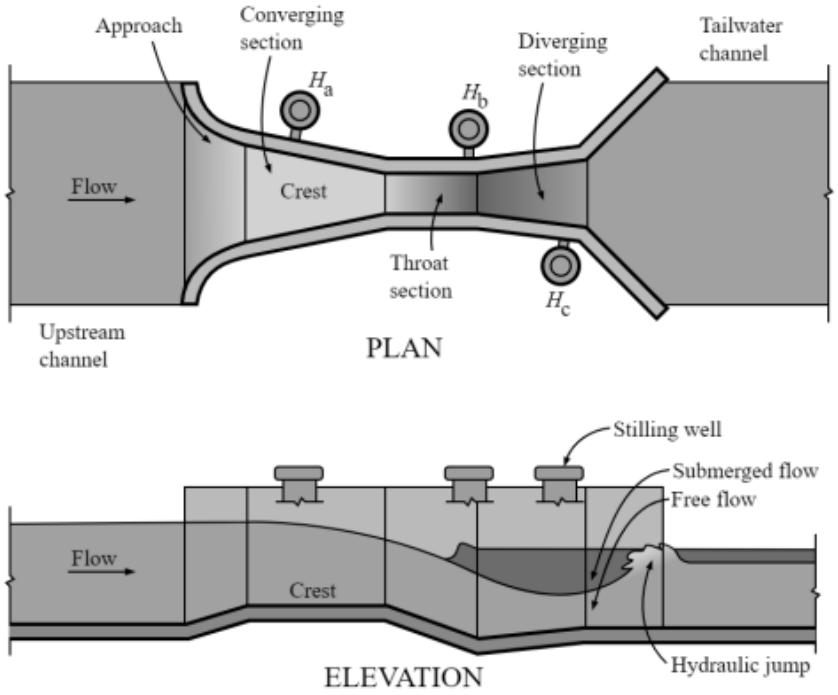



Figure 1 – Parshall Flume (HEYRANI, 2022).

The flume operates based on the specific energy principle, creating a critical flow condition at the throat of the structure. Upstream of this point, at a location known as the control section, the discharge can be estimated through empirical equations (Equation 1) that relate the water surface elevation (free surface height) to the volumetric flow rate.

$$Q = C.h^n \tag{1}$$

Where $Q$ is the flow rate (m³/s); $h$ is the free surface depth (m); $C$ and $n$ are empirical coefficients associated with Parshall's Flume dimensions and geometry.

### 2.2 Surface tension and its implications in wastewater flow

Surface tension is an interfacial property that represents the cohesive force between molecules at the surface of a liquid. In sanitary sewage, the presence of organic substances, surfactants, and suspended solids significantly reduces the surface tension compared to potable water, with values typically ranging between 0.030 and 0.050 N/m (CHENG et al., 2018; ZHOU et al., 2020). This reduction affects the stability of the air–liquid interface, promoting the formation of surface instabilities, bubbles, and recirculation zones. Such effects influence the flow dynamics within hydraulic flumes, directly impacting flow measurements obtained by ultrasonic and pressure-based sensors, which rely on the regularity of the free surface for accurate readings (WU et al., 2017).

### 2.3 CFD applications in hydraulics and sanitation

Computational Fluid Dynamics (CFD) has become an indispensable tool for analyzing complex flow phenomena in hydraulic and sanitary engineering. Its ability to represent in detail regime transitions, vortex formation, and multiphase behavior makes it especially useful in studies involving flumes, weirs, and energy-dissipating structures (FERZIGER & PERIĆ, 2002; VERSTEEG & MALALASEKERA, 2007). In the context of Parshall flumes, CFD modeling enables three-dimensional visualization of velocity, pressure, and turbulence fields, while also allowing the assessment of the influence of fluid properties such as surface tension, something unfeasible through purely experimental methods. Recent studies have demonstrated the effectiveness of multiphase and interface-tracking models, such as the Volume of Fluid (VOF) method, in capturing the free-surface dynamics of sanitary flows in open channels (KARAMI et al., 2022).

### 2.4 Interface and turbulence modeling: VOF and k-ω SST methods

Among the numerical methods used to simulate two-phase flows, the Volume of Fluid (VOF) method stands out for its accuracy in identifying the interface between immiscible fluids, being widely applied in free-surface modeling. The VOF method solves the volume fraction of each phase in every computational cell, enabling the simulation of surface instabilities and air entrainment with high fidelity (HIRT & NICHOLS, 1981). Regarding turbulence modeling, the Shear Stress Transport (k-ω SST) model has been frequently employed in studies of flows in flumes, channels, and hydraulic structures due to its robustness in predicting regions with strong shear gradients, such as the throat of a Parshall flume. Developed by Menter (1994), this model combines the strengths of the standard k-ε and k-ω models, making it well-suited for near-wall modeling and transitional flow conditions.

## 3 Methodology

As previously mentioned, the methodology of this study was based on the CFD modeling of sanitary effluent flow through a Parshall flume. In this context, ANSYS Fluent was selected as the computational tool for conducting the simulations.

Initially, a virtual geometric model of the Parshall flume (Figure 2) was created directly within the ANSYS Fluent interface. The flume dimensions were defined based on a real structure installed at the wastewater treatment plant (WWTP) of a medium-sized Brazilian city. Table 1 presents the main geometric characteristics of the developed virtual flume model.

The geometry was modeled considering symmetry with respect to the vertical longitudinal plane, aiming to reduce computational costs. The three-dimensional domain extended from the inlet section to the region downstream of the throat. The computational mesh was predominantly composed of hexahedral elements, with refinement applied near the free surface and in the throat region, where higher velocity gradients are expected. A mesh independence study was carried out to ensure that the numerical solution remained stable and consistent regardless of the element size.

Table 1 – Parshall flume geometric configuration.

| *Parameter* | *Value (m)* |
|---|---|
| Inlet/Outlet Width | 1.610 |
| Inlet/Outlet Length | 3.500 |
| Converging/Diverging Section Length | 3.500 |
| Throat Width | 1.000 |
| Throat Length | 2.000 |
| Flume Height | 1.000 |

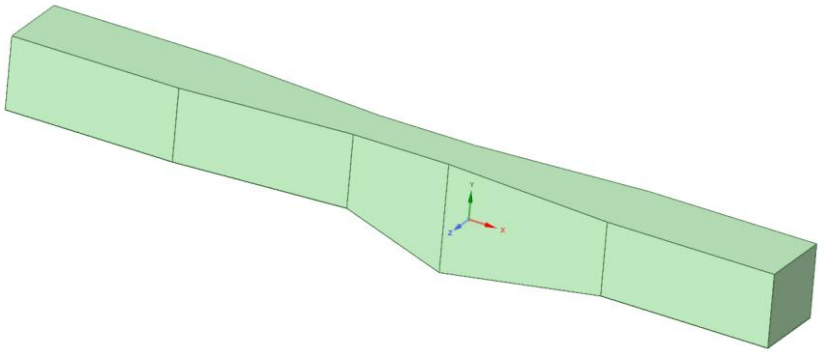


Figure 2 – Parshall Flume geometry.

Regarding the boundary conditions, a constant velocity rate prescribed at the inlet, based on typical values for domestic sewage in urban areas. At the outlet, a zero-gauge pressure condition was applied to simulate atmospheric discharge. The flume walls were treated as no-slip surfaces, while the free surface was modeled as a deformable air–liquid interface, enabling the simulation of surface variations and wave formation.

To represent the multiphase behavior of the air–sewage interaction, the Volume of Fluid (VOF) method was adopted, which tracks the volume fraction of each phase within the computational cells. Surface tension was included as a variable parameter, with values ranging from 0.030 to 0.050 N/m, as reported in relevant literature on wastewater hydraulic properties. Turbulence effects were captured using the Shear Stress Transport (SST) k-ω model, which is particularly suitable for flows with strong shear gradients and adverse pressure conditions, such as those found near the flume throat.

The numerical simulations were conducted until the residuals of the continuity, momentum, and volume fraction equations fell below $10^{-4}$ indicating solution convergence. The main parameters to be measured in the simulations were the free surface height at the measurement point recommended by the literature for the Parshall flume, and the sewage flow rate along this hydraulic structure. The height was automatically recorded by assigning a monitoring point within ANSYS Fluent. The flow rate was calculated through the implementation of a User-Defined Function (UDF) based on the generalized mathematical model of the flume, as presented in Equation 1.

$$Q = b.\sqrt{2g}.h^{3/2} \tag{1}$$

Where $Q$ is the volumetric flow rate through the Parshall flume (m³/s), $b$ is the width of the throat section of the Parshall flume (m), $g$ is the gravity acceleration (m/s²), and $h$ is the critical depth of the water surface at the throat section (m).

To enhance the graphical analysis of flow behavior and the identification of surface instabilities and/or recirculation zones resulting from variations in surface tension across the simulated wastewater scenarios, the free surface profile along the flume was systematically monitored. This was achieved through the generation of longitudinal plots of the water surface depth along the modeled hydraulic structure. To validate the results, the simulated water surface profiles were compared with experimental data available in the literature for Parshall flumes of similar geometry and flow characteristics, confirming the reliability of the adopted modeling approach.

# 4 Results and discussions

## 4.1 General results and CFD models

The computational models developed in ANSYS Fluent enabled the simulation of the hydraulic behavior of sanitary effluent within a Parshall flume under different surface tension conditions. Figure 3, 4 and 5 presents an example of numerical modeling results, highlighting three key hydraulic parameters: mean flow velocity, turbulent kinetic energy ($k$), and Reynolds number distribution. These parameters are critical to understanding the flow structure, particularly in identifying regions of velocity gradients, turbulence generation, and potential transitions in flow regimes along the flume.

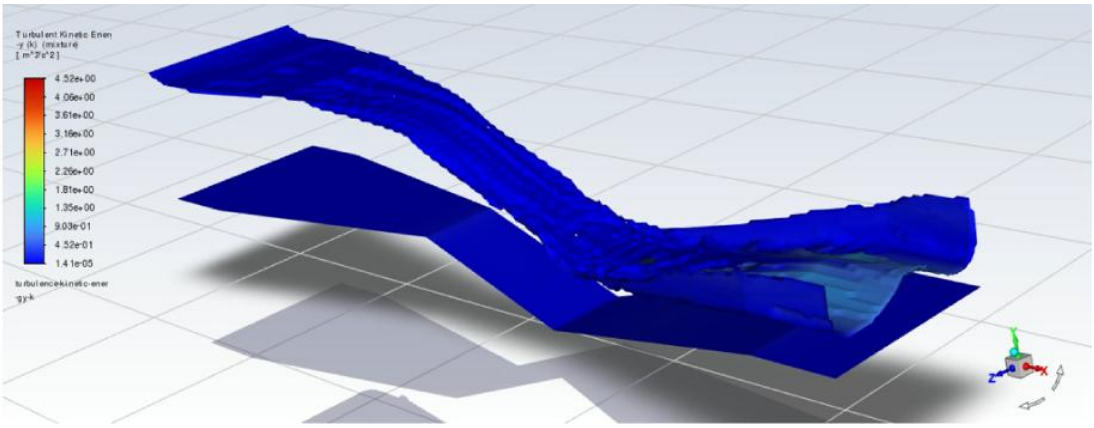



Figure 3 – Velocity model in Parshall Flume (TS = 0.050 N/m).

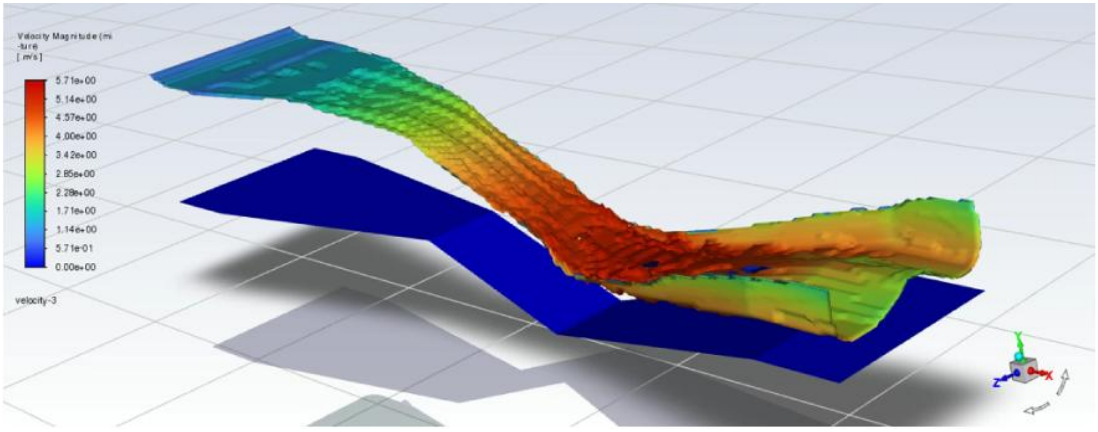



Figure 4 – Turbulent Kinetic Energy in Parshall Flume (TS = 0.050 N/m).

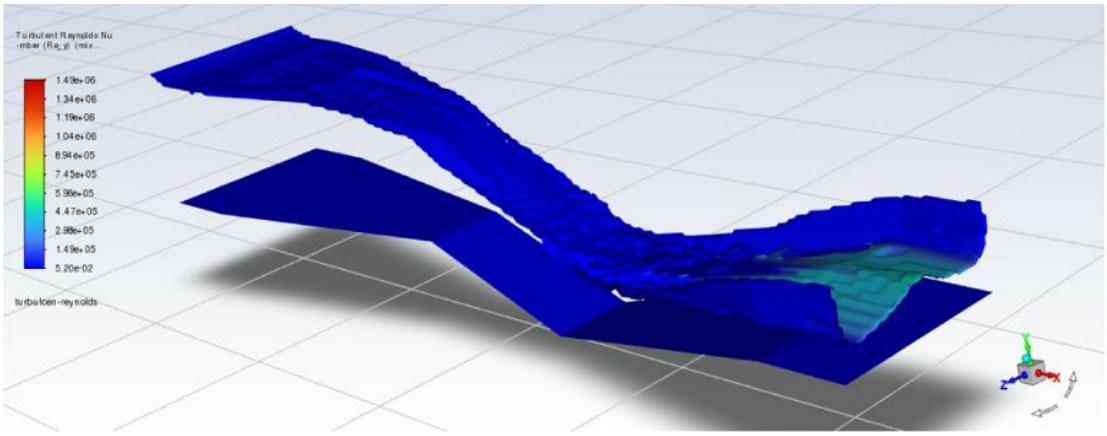



Figure 5 – Reynolds Number in Parshall Flume (TS = 0.050 N/m).

It is important to emphasize that the figures above provide merely as a visual example of the type of output generated. To facilitate interpretation and enhance visual clarity, the simulation results were subsequently processed and transformed into stage–discharge plots (flow rate vs. free surface elevation). These plots, representing the quantitative core of this study, are discussed in greater detail in the following sections.

The simulations were performed considering a two-phase (water–air) flow with the free surface captured through the Volume of Fluid (VOF) method, while turbulence effects were resolved using the $k$-$\omega$ SST model. Boundary conditions included a uniform inlet velocity profile, atmospheric outlet pressure, and rough no-slip walls, replicating the hydraulic characteristics typically observed in operational Parshall flumes. Each simulation was run for 100-time steps with a temporal resolution of 0.001 s to ensure transient features were adequately captured.

Three distinct surface tension values (0.030 N/m, 0.040 N/m, and 0.050 N/m) were assigned to represent different wastewater conditions commonly reported in the literature (domestic, mixed, and industrial, respectively). An additional reference simulation with a surface tension of 0.072 N/m, corresponding to standard water, was also conducted to provide a comparative baseline. This modeling approach allowed for a detailed evaluation of how surface tension influences flow stability, recirculation patterns, and measurement accuracy in Parshall flumes.

### 4.2 Comparative Analysis of Stage–Discharge Relationships for Different Surface Tensions

The quantitative evaluation of flow behavior in the Parshall flume was carried out by examining the relationship between the free surface elevation at the standard measurement point and the corresponding flow rate through the structure. This relationship is fundamental for characterizing flow hydraulics and verifying how surface tension influences the stability and accuracy of flow measurement.

Figures 6 through 9 present the results for each surface tension condition analyzed. Figure 6 shows the case with the lowest surface tension (0.030 N/m), Figure 7 refers to the intermediate condition (0.040 N/m), Figure 8 corresponds to the higher wastewater-related tension (0.050 N/m), and Figure 9 illustrates the reference condition with a surface tension of 0.072 N/m, representing standard water. Each dataset contains 100 instantaneous values obtained from the transient CFD simulations, allowing the assessment of natural flow variability.

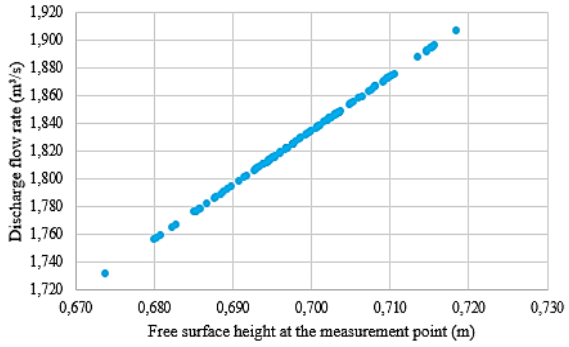



Figure 6 – Relation with free flow rate discharge and free surface height in TS of 0.030 N/m.

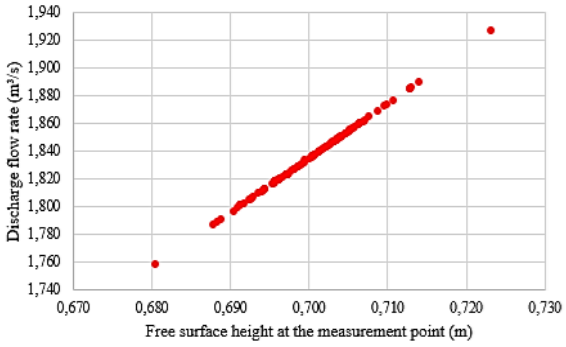



Figure 8 – Relation with free flow rate discharge and free surface height in TS of 0.050 N/m.

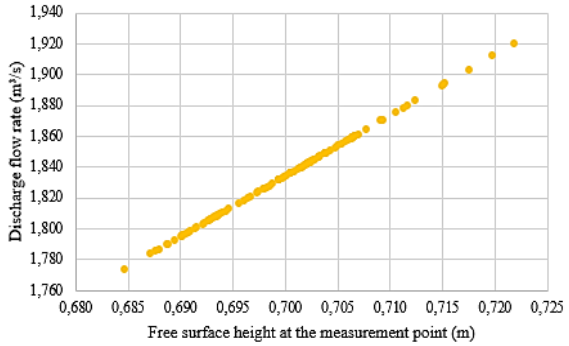



Figure 7 – Relation with free flow rate discharge and free surface height in TS of 0.040 N/m.

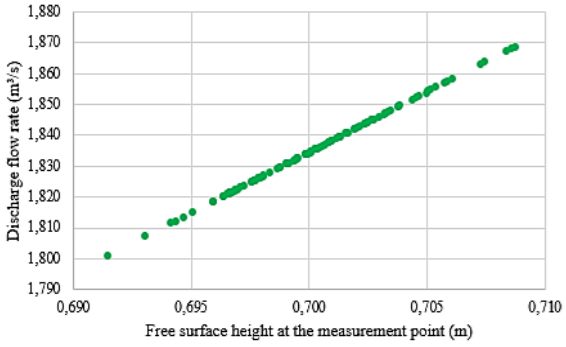



Figure 9 – Relation with free flow rate discharge and free surface height in TS of 0.072 N/m.

A clear trend was observed across all scenarios: as surface tension decreases, the variability in free surface elevation at the measurement point increases. For the 0.030 N/m case (Figure 6), corresponding to domestic wastewater, the stage–discharge data showed the widest scatter, indicating higher surface instabilities and small oscillations in flow depth. The 0.040 N/m case (Figure 7), representing mixed wastewater, exhibited intermediate behavior, with fluctuations reduced compared to 0.030 N/m but still greater than those observed for higher surface tensions. The 0.050 N/m condition (Figure 8), commonly associated with industrial effluents, presented a smoother relationship, with smaller variations and a profile closer to the theoretical expectation for steady flow. Finally, the reference condition (0.072 N/m) (Figure 9) exhibited the most stable behavior, where the stage–discharge points aligned closely, reflecting a well-defined and repeatable hydraulic response.

These results highlight that surface tension plays a non-negligible role in flow measurement accuracy. Lower surface tensions tend to promote interface disturbances, leading to oscillations in free surface elevation that may affect real-time measurement devices such as ultrasonic or pressure-based sensors. Conversely, higher surface tensions contribute to stabilizing the flow profile, reducing measurement uncertainty.

### 4.3 Identification of Flow Instabilities and Recirculation Zones

The identification of flow instabilities and recirculation zones within the Parshall flume was carried out using two complementary approaches. The first approach consisted of a qualitative analysis based on visual inspection of the animations and CFD models generated in ANSYS Fluent. This analysis allowed for the direct observation of regions with velocity reversals, turbulent structures, and free surface oscillations, which are indicative of flow separation and interface instability.

The second approach aimed at providing a more systematic and quantitative representation of these phenomena. For each surface tension scenario, 100 free surface elevation values were directly extracted from ANSYS Fluent at equally spaced points along the longitudinal profile of the flume. These data were then plotted as longitudinal free surface profiles (Figure 10), enabling clearer identification of localized fluctuations compared to visual inspection alone.

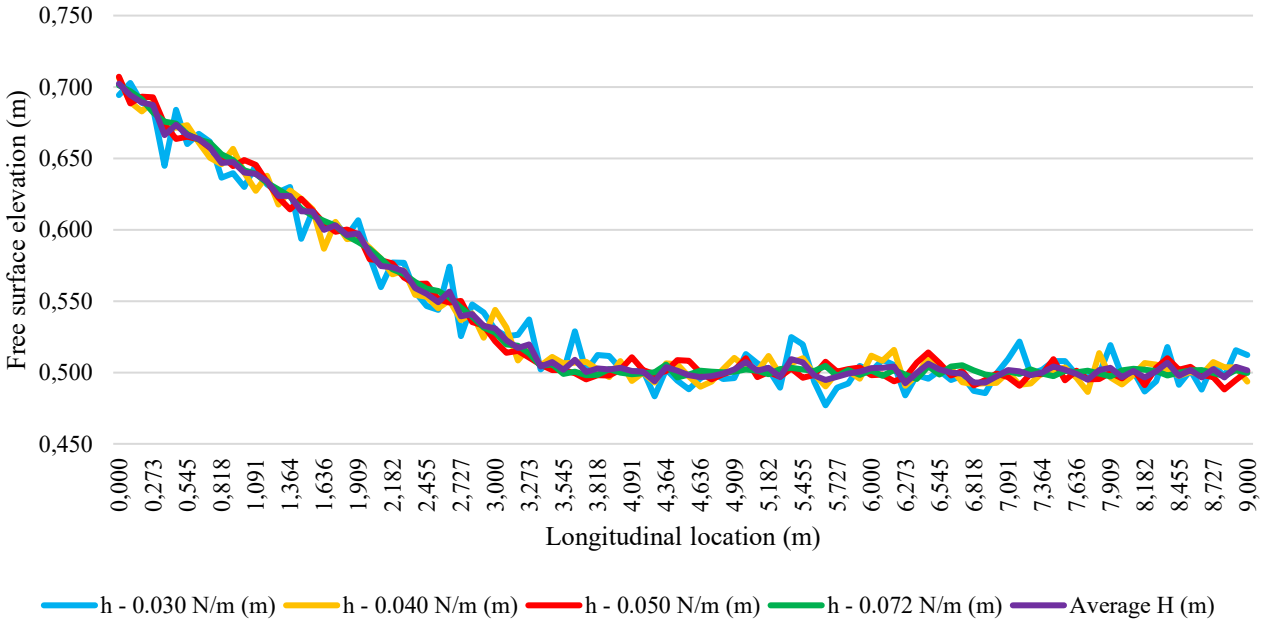



Figure 10 – Free surface longitudinal profile with different surface tensions.

Figure 10 illustrates the longitudinal free surface profiles for the different surface tension scenarios, where localized instabilities can be identified primarily downstream of the throat region (approximately between 2.5 m and 4.5 m). These fluctuations are characterized by small-scale oscillations and deviations from the average profile, particularly pronounced for the lowest surface tension case (0.030 N/m), indicating increased interface deformation and localized recirculation. Downstream of approximately 5.0 m, the profiles converge and exhibit

reduced variability, suggesting a gradual dissipation of these instabilities as the flow reestablishes equilibrium. Such behavior confirms that surface tension directly influences flow stability, with lower values promoting more noticeable free surface disturbances.

To further quantify these instabilities, statistical indicators were calculated for each surface tension condition, including variance, standard deviation, and the coefficient of variation. These metrics provided an objective measure of free surface variability relative to the mean profile, making it possible to compare instability intensity among scenarios. Lower surface tension conditions (0.030 and 0.040 N/m) exhibited higher coefficients of variation, indicating more pronounced free surface oscillations, while the higher surface tension cases (0.050 and 0.072 N/m) showed smaller variability and smoother flow behavior. Figure 11 illustrates the standard deviation of the free surface elevation measurements along the flume for a representative mean flow condition.

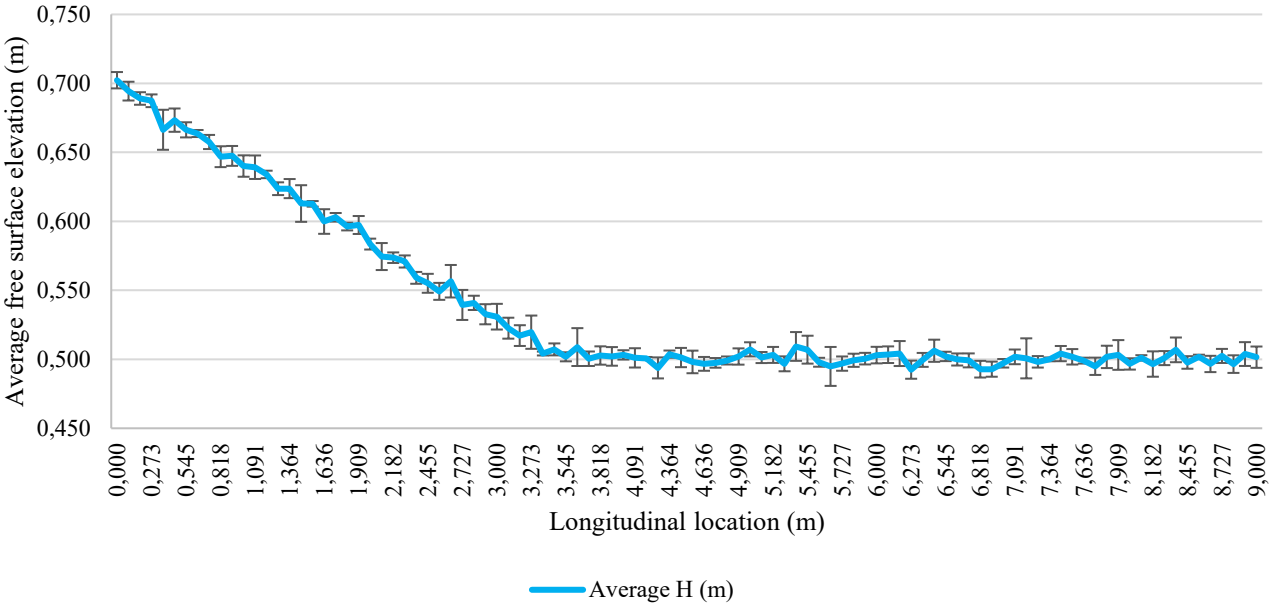



Figure 11 – Standard deviation along the Parshall Flume.

Figure 11 presents the average free surface profile along the flume, accompanied by the standard deviation at each measurement point, which highlights the spatial distribution of flow instabilities. The highest variability is observed in the throat and immediate downstream transition region (approximately between 2.5 m and 4.5 m), where flow acceleration and shear promote free surface disturbances and localized oscillations.

Upstream of the throat, fluctuations are smaller due to the subcritical approach flow, while downstream of approximately 5.0 m, the flow gradually stabilizes, and the standard deviation decreases, indicating the dissipation of surface disturbances. This spatial pattern reinforces that the throat region is the most sensitive to variations in surface tension and flow conditions, directly influencing the stability of the free surface and, consequently, the reliability of level-based flow measurements.

This graphical representation highlights the spatial distribution of instabilities, showing that fluctuations tend to concentrate in specific regions, particularly near the throat and downstream transition zones, where velocity gradients and flow separation promote free surface disturbances. The amplitude and extent of these fluctuations decrease with increasing surface tension, reinforcing the role of interfacial forces in stabilizing the flow.

This combined qualitative–quantitative approach reinforces the conclusion that surface tension significantly influences the stability of free surface flows in Parshall flumes and underscores the importance of considering these effects in flow measurement and hydraulic design.

### 4.4 Comparative Evaluation with Reference Surface Tension and Practical Implications for Flow Measurement

The results obtained for the three wastewater-related surface tension values (0.030, 0.040, and 0.050 N/m) were compared with the reference scenario using the standard water surface tension of 0.072 N/m. This comparison

sought to quantify how interfacial forces affect the hydraulic performance of the Parshall flume and, consequently, the accuracy of flow measurement based on stage–discharge relationships.

The reference scenario (0.072 N/m) presented the most stable hydraulic behavior, with a well-defined free surface profile and minimal fluctuations. The stage–discharge curve for this case (Figure 9) showed strong alignment with the expected theoretical relationship, validating the computational model. In contrast, simulations with lower surface tension values exhibited increasing free surface oscillations and localized flow disturbances. The 0.030 N/m case, representing typical domestic wastewater, showed the highest variability, followed by the mixed wastewater condition (0.040 N/m). Industrial wastewater (0.050 N/m) displayed intermediate behavior, closer to that of standard water, yet still exhibiting noticeable deviations in the throat region and downstream transitions.

These differences are quantitatively reflected in the statistical indicators of free surface instability discussed earlier. The coefficient of variation and standard deviation profiles (Figure 11) clearly show that lower surface tension correlates with greater hydraulic variability, particularly in regions prone to flow separation and interface deformation. Such instabilities have direct implications for field measurements: sensors based on ultrasonic or pressure-based techniques may misinterpret oscillating surfaces as actual flow variations, introducing additional uncertainty into flow calculations.

From an engineering perspective, these findings emphasize that surface tension differences between clean water and actual wastewater should not be neglected in numerical modeling or experimental calibration of Parshall flumes. While these effects may not significantly alter mean discharge under steady-state conditions, they influence the reliability of real-time measurements and may require corrective factors or filtering algorithms in automated systems.

The results obtained in this study, particularly regarding free surface variability and hydraulic behavior within the Parshall flume, were compared with experimental and numerical data available in the literature. Classic studies on Parshall flumes, such as those by Bos (1989) and ISO 9826 (1992), describe hydraulic behavior under uniform flow conditions using clean water and indicate that, under such conditions, the stage–discharge curve exhibits excellent repeatability and surface stability, with average deviations below 2%.

However, more recent research involving flows with distinct physical and chemical characteristics, as presented by Wu et al. (2017) and Karami et al. (2022), indicate that properties such as viscosity and surface tension can alter free surface stability, particularly in the throat region, affecting level measurement. In these studies, increases in free surface fluctuations ranging from 5% to 15% were observed in wastewater flows, depending on the concentration of surfactants and suspended solids.

The numerical results obtained in this work reproduced these trends: reducing surface tension to values characteristic of domestic sewage (0.030 N/m) resulted in up to a 12% increase in local free surface variability, with more pronounced recirculation zones downstream of the throat. For intermediate surface tensions (0.040 N/m), the behavior was similar but with fluctuations reduced to about 7%, while the highest surface tension (0.050 N/m) exhibited behavior close to the reference scenario with clean water (0.072 N/m), with variations below 4%.

Furthermore, the numerically obtained stage–discharge curve showed good agreement with experimental data for flumes of equivalent dimensions, as reported by Bos (1989) and ISO 9826 (1992), with average deviations below 5% for all simulated conditions. This agreement reinforces the suitability of the numerical modeling adopted, as well as the importance of considering specific physical properties of effluents in flow measurement studies.

In practical terms, the results support the conclusions of Wu et al. (2017) that pressure- and ultrasound-based sensors may present unstable readings when exposed to free surface conditions with high fluctuations. This study expands on that discussion by quantifying the direct influence of surface tension, demonstrating that proper parameterization of this property in CFD models is essential to adequately represent field conditions in sanitary sewer systems.

# 5 Conclusions

This study investigated the influence of surface tension on the hydraulic behavior of sanitary effluent flow through a Parshall flume using Computational Fluid Dynamics (CFD) simulations. The Volume of Fluid (VOF) method was applied to capture the free surface dynamics, and turbulence was modeled using the k–ω SST model,

enabling detailed analysis of flow instabilities and recirculation zones under different surface tension scenarios.

The results demonstrated that lower surface tensions, representative of domestic wastewater (0.030 N/m), produced increased free surface variability, localized instabilities, and more pronounced recirculation downstream of the throat region. Intermediate (0.040 N/m) and higher (0.050 N/m) surface tensions exhibited reduced fluctuations, with the latter presenting a flow pattern close to the reference condition for clean water (0.072 N/m). These findings are consistent with experimental and numerical studies available in the literature, confirming that fluid interfacial properties directly influence flow stability and, consequently, the reliability of level-based flow measurements in Parshall flumes.

Finally, the study emphasizes the need to consider effluent-specific physical properties, particularly surface tension, when applying CFD models for design, calibration, or operational analysis of flow measurement systems. Proper parameterization of these properties ensures more realistic numerical predictions and supports the development of robust sensor calibration strategies to minimize measurement uncertainties under real wastewater conditions.

**Acknowledgements.** The authors acknowledge CAPES – Brazilian Federal Agency for Support and Evaluation of Graduate Education – for funding the research carried out, as well as the Graduate Program in Mechanical Engineering of the School of Mechanical Engineering at the Federal University of Uberlândia for its support and guidance.

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