

Experimental investigation of two-phase flow characteristics of nitrogen-CMC solution and nitrogen-XG solution in A 0.8 mm X 0.8 mm square capillary tube in a horizontal position

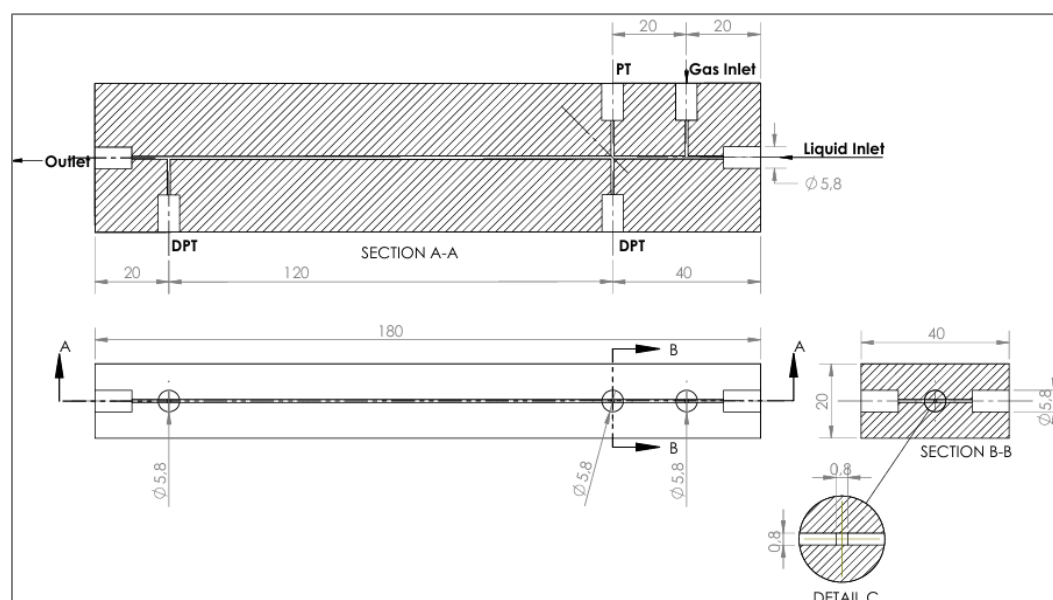
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Highlights:

- Two-phase nitrogen–non-Newtonian gas–liquid flow was experimentally investigated in a horizontal 0.8 × 0.8 mm square capillary tube.
- Liquid superficial velocity (J_L) governed the baseline pressure gradient, while gas superficial velocity (J_G) intensified $\Delta p/L$ after flow regime transition.
- Increasing polymer concentration (0.2–0.4 wt%) elevated pressure gradients and advanced flow transitions, with xanthan gum showing stronger shear-thinning effects than carboxymethyl cellulose.
- Flow pattern maps identified stable bubbly/plug and annular regimes and delineated churn regions, providing operational guidance for small-channel hydrogen transport systems.

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Abstract

Two-phase gas–liquid flow in small channels is important in mini/micro heat exchangers, flow chemistry and hydrogen transport subsystems (such as fuel cell manifolds and electrolyzers), which require control of pressure loss and stable regimes. However, there is still a limited database of combinations of nitrogen gas and non-Newtonian fluids in square capillary pipes, even though shear-thinning properties can shift the transition map and increase sensitivity to superficial velocity. This study aims to address this issue by experimentally characterizing pressure gradients and flow patterns. Methods include testing nitrogen–polymer solutions in horizontal 0.8 × 0.8 mm

square capillary tubes. The test fluids are carboxymethyl cellulose (CMC) and xanthan gum (XG), at concentrations of 0.2% and 0.4% by mass. The operating range included gas superficial velocity (J_G) of 0.3–7.8 m/s and liquid superficial velocity (J_L) of 0.03–1 m/s. The pressure gradient ($\Delta p/L$) was measured differentially, while the interface configuration was recorded for regime identification and flow pattern mapping. The results show that J_L primarily controls the base level of $\Delta p/L$, while J_G triggers a further increase once the transition threshold has been passed. Increasing the concentration from 0.2% to 0.4% raised $\Delta p/L$ in all J_G – J_L combinations and advanced the transition. XG exhibited stronger shear thinning than CMC, resulting in a generally lower $\Delta p/L$, narrower churn regions and a more gradual transition from slug to annular flow. Flow pattern maps confirm the presence of a bubbly/plug domain at low J_G , churn at medium and high J_G – J_L combinations, and annular flow at low J_L and high J_G . These findings provide an operating window to avoid churn and direct the system towards either stable bubbly/plug or stable annular flow. This is highly relevant for designing low- to medium-pressure hydrogen transport systems in small channels.

Keywords: Two-phase flow; Carboxymethyl cellulose (CMC); Xanthan gum (XG); Pressure gradient; Flow pattern

1. Introduction

Two-phase gas-liquid flow in mini- and micro-sized channels is central to various processes and energy applications, including micro heat exchangers, microreactors, lab-on-a-chip devices, and modern electrochemical systems. In small geometries, pressure gradients are a key parameter as they directly determine the power requirements of pumps and compressors, as well as the stable operating limits and flow pattern transition maps [1], [2]. Changes in the dominance of interfacial forces, as well as the effects of confinement and wetting limitations, mean that conventional two-phase correlations (as applied to large pipes) are no longer adequate. This requires the development of specific databases and modelling for mini/micro channels [3], [4].

Recently, research attention has shifted from gas–Newtonian liquid systems to combinations of gas and non-Newtonian liquid. This is a relevant area of research because many process fluids (polymer solutions, slurries and biofluids) exhibit shear-thinning and viscoelastic behaviour. This can alter slug length, meniscus dynamics and the equilibrium between friction and capillary loss [5], [6]. In square channels with corners that retain the film, non-Newtonian effects modulate the wall film thickness and slug–film interactions, thereby significantly affecting the pressure gradient [7]. In this context, carboxymethyl cellulose (CMC) and xanthan gum (XG) are considered reliable model fluids. At low concentrations (0.2–0.4% by mass), CMC and XG exhibit shear-thinning behaviour that can be accurately modelled using empirical equations [8], [9]. To generalise non-Newtonian dynamics, the Metzner–Reed generalised Reynolds number framework is often used to map pressure loss data across flow indices and consistency [10], [11].

The scientific and technological urgency of this study is directly related to the accelerated adoption of hydrogen as a clean energy carrier. Recent reports indicate that the global capacity for hydrogen is increasing, as are large-scale projects, requiring efficient and reliable system designs [12], [13]. In both the upstream and downstream sections of the hydrogen supply chain, two-phase flow occurs in various subsystems, such as water and gas management in fuel cell channels and polymer membrane electrolysis. Here, phase distribution, differential pressure and flooding determine performance and degradation [14], [15], [16]. Additionally, bubble evolution and gas release in electrolyser channels affect pressure losses and electrode utilisation [17], [18]. Furthermore, slug or plug flow of gas–liquid mixtures containing condensate/alkali in hydrogen transport pipes can trigger pressure oscillations and increased pressure losses [19]. While real systems typically involve water/electrolyte mixtures (Newtonian), using non-Newtonian fluids (e.g. CMC and XG) on a mini/micro scale offers different physical insights. For instance, shear-thinning behaviour can alter the local effective viscosity throughout the slug–film cycle, potentially shifting the flow pattern map and pressure loss scale. In other words, gas–CMC experiments in small channels provide a means of understanding the limits of design when process fluids are not Newtonian, which is an increasingly common occurrence in modern process intensification, flow chemistry and electrochemistry technologies [5], [6], [7].

Experimental studies have confirmed that the geometry of small pipes and capillaries, the physical properties of liquids (e.g. viscosity and interfacial tension) and the orientation of the pipes (e.g. horizontal or inclined) have a strong influence on flow patterns, void fraction and pressure gradients [20], [21], [22], [23], [24], [25]. These studies demonstrate the sensitivity of the pressure gradient to gas/liquid superficial velocity (J_G , J_L) and changes in viscosity (e.g. glycerine mixtures),

even at inclinations as small as 5°–45°. These findings reinforce the need for a new database on capillary-sized square channels, since the angle effect (film trapping) and cross-sectional anisotropy differ from those of the more commonly studied circular pipes.

This study therefore focuses on the two-phase flow of nitrogen–CMC and XG solutions (0.2% and 0.4%) in a 0.8 mm × 0.8 mm square capillary pipe in a horizontal orientation, to address this knowledge gap. Nitrogen was chosen as an inert and measurable gas, while CMC and XG solutions were chosen as non-Newtonian fluids that are rheologically stable at low concentrations [8], [9], [10]. This configuration enables the scientific mapping of the influence of J_G and J_L on pressure gradients and pattern transitions (including plug, slug-annular, churn and thin annular) in square geometries.

In terms of urgency, the proposed results will enrich the existing literature on gas pressure gradients in small, relatively confined non-Newtonian liquid, particularly those with square cross-sections. They will also provide the necessary experimental benchmarks to validate the latest correlations (CFD). Practical benefits include designing manifolds and distribution channels for mini/micro devices, controlling pattern transitions to suppress pressure spikes and optimising operating conditions to minimise pump power consumption below the two-phase stability limit [5], [6], [7].

Specifically, this study aims to measure and plot the two-phase pressure gradient of nitrogen and CMC and XG solutions in a horizontal square channel measuring 0.8 mm × 0.8 mm for representative J_G and J_L ranges. The effect of CMC and XG concentrations (0.2% and 0.4%) as strong non-Newtonian indicators on flow pattern changes and pressure losses will also be examined. Thus, this study is expected to address some gaps in the experimental data and advance understanding of non-Newtonian two-phase phenomenology at the capillary scale. It will also provide a basis for developing more universal correlations and design tools.

In the present work, nitrogen is employed as the gas phase. Nitrogen is widely used as an inert and safe surrogate for hydrogen in laboratory studies, because it allows similar ranges of superficial gas velocity and operating pressure to be explored without the safety constraints associated with hydrogen handling. The experiments in this study are interpreted as a model for low- to medium-pressure hydrogen systems. However, it is emphasized that the results are intended to provide qualitative trends and scaling guidance for gas–liquid management in small channels, rather than a one-to-one quantitative map for any particular hydrogen device.

2. Methodology

This study used two types of fluid, gas and liquid. Nitrogen was used as the gas-phase fluid, while four solutions were used as the liquid phase (distilled water mixed with 0.2% and 0.4% concentrations of CMC and XG). Data on the physical and rheological properties of CMC and XG solutions are presented briefly in Table 1 and Table 2. Data on the viscosity versus shear stress of CMC and XG solutions can be found in the paper by [26]. The graph shows that aqueous solutions of CMC (0.2% and 0.4%) and XG (0.2% and 0.4%) exhibit shear thinning properties.

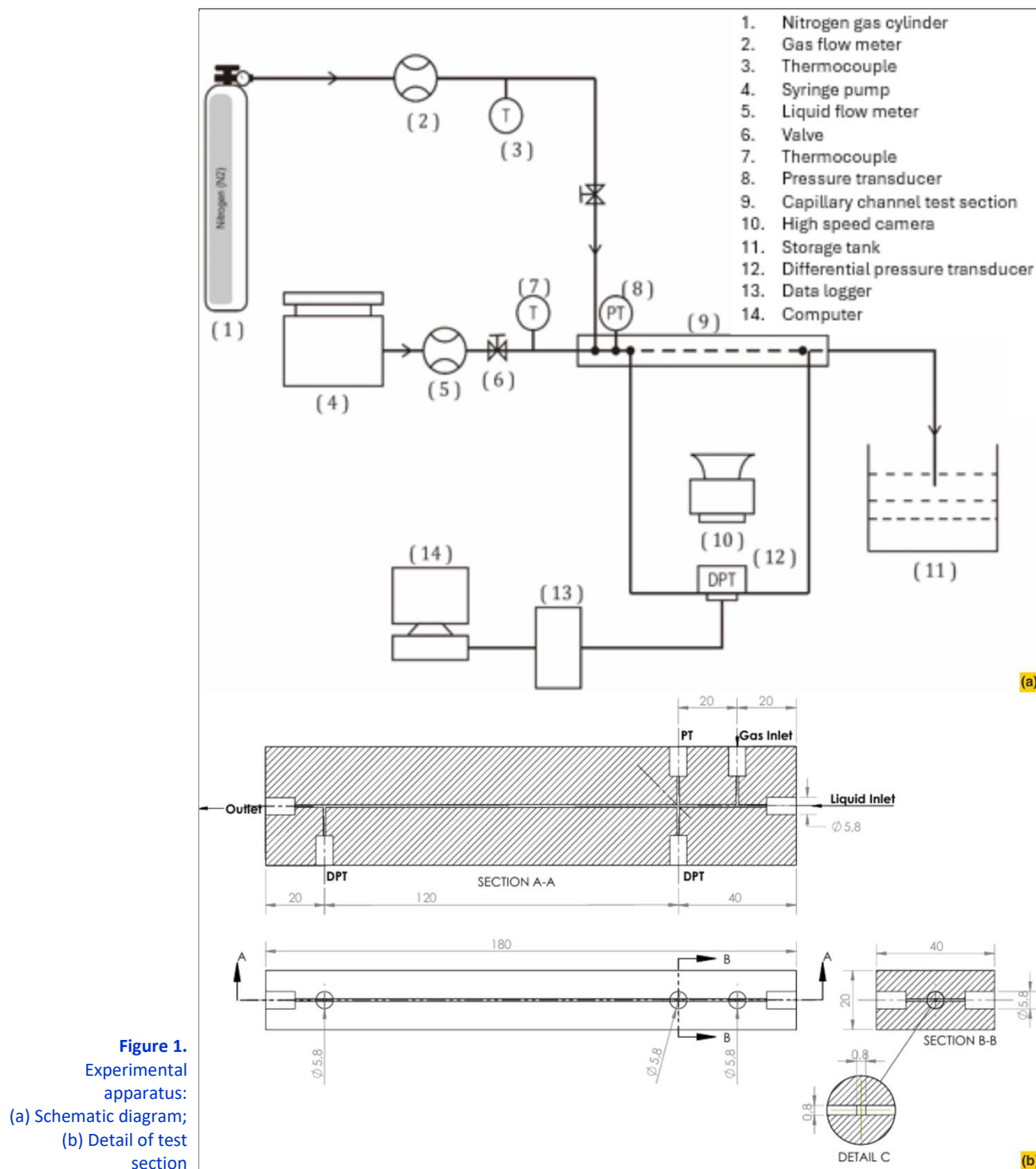
Figure 1 shows the experimental research apparatus. This consists of a schematic diagram (a) and details of the test section (b). This shows that the installation consists of a nitrogen gas cylinder, a gas flow meter, a syringe pump, pressure transducer, a capillary channel test section, a high-speed camera, a storage tank, a differential pressure transducer, a data logger and a computer. The test section is a square channel with a side length of 0.8 mm. The high-speed camera used is a Phantom Miro C 321. Video data of the flow pattern is obtained from this camera and is

Table 1.
Physical properties
(representative, 25 °C)
[27]

Solution	Density, ρ [kg/m ³]	Surface tension, σ [milli-Newton/m]
CMC 0.2%	1000	75
CMC 0.4%	1015	80
XG 0.2%	1000	74
XG 0.4%	1015	83

Table 2.
Rheological parameters
& apparent viscosity
ranges

Solution	Flow index, n [-]	Consistency index, k [Pa·s ^{n}]	μ_{app} (@ $\dot{\gamma} \approx 10^2$ s ⁻¹)	Behavior
CMC 0.2%	~0.6–0.8	~10 ⁻² –10 ⁻¹	~10–50 mPa·s	Shear-thinning
CMC 0.4%	~0.5–0.7	~10 ⁻¹ –10 ⁰	~30–150 mPa·s	Shear-thinning stronger than 0.2%
XG 0.2%	~0.2–0.4	~10 ⁻¹ –10 ⁰	~20–100 mPa·s	Strong shear-thinning
XG 0.4%	~0.15–0.35	~10 ⁰ –10 ¹ (low-shear)	~40–200 mPa·s	Very strong shear-thinning



then processed into a flow pattern map. The pressure transducer used is a Valdyne P55-4N-1-50-S-4-A model, which measures the pressure difference between the inlet and outlet sides of the test section. This differential pressure transducer obtains pressure drop data in volts. This data is then converted into kPa using a pre-prepared calibration equation. The pressure drop data was converted into pressure gradient data by dividing it by the effective length of the test section (0.12 meters). The research was conducted under adiabatic conditions. The superficial velocity of the gas and liquid was set to a range of 0.3–7.8 m/s and 0.03–1 m/s, respectively.

Nitrogen gas flows from the gas cylinder to the test section via a gas regulator, a flow meter and a T-junction. The gas pressure in the regulator is set at approximately 2 bars. It then flows to the flowmeter, where the flow rate is adjusted to achieve the desired superficial velocity according to the research matrix. It then flows through a 4 mm inner diameter hose to the T-junction. At the T-junction, the gas meets the liquid before entering the test section. While the liquid, which is a non-Newtonian fluid solution, is pumped directly into the test section by a Syringe pump. This

pump is equipped with a flow meter. Data loggers and computers are used to convert analogue data into digital data and to store and process data, respectively.

3. Results

3.1. Pressure Gradient

In capillary-sized channels, the pressure gradient in two-phase gas–liquid flow is the sum of the friction component (Δp_f) and the acceleration component (Δp_a). Due to the horizontal position, the hydrostatic component can be ignored. The two main controllers of pressure gradient behaviour are J_L and J_G . An increase in J_L increases the flow rate and the fluid's effective viscosity (especially for non-Newtonian polymers), thereby increasing Δp_f . An increase in J_G adds interfacial shear and acceleration contributions while altering the flow pattern (from plug/slug to churn/annular).

As the fluids tested are non-Newtonian (CMC and XG), the apparent viscosity (μ_{app}) decreases as the shear rate increases (shear thinning). Qualitatively, increasing J_G or J_L can decrease μ_{app} , thereby suppressing part of the increase in Δp_f . The interplay between the decrease in μ_{app} due to shear thinning and the increase in interfacial shear and acceleration due to gas explains the non-linear slope of the curve, which occasionally takes the form of a slight U-shape or plateau at medium J_G . The type of polymer also plays an important role. CMC and XG have different flow indices and consistencies. XG generally exhibits greater shear thinning at equivalent concentrations, meaning that within the experimental shear rate range, the pressure gradient of XG tends to be lower than that of CMC.

Figure 2 (CMC 0.2%) shows that the pressure gradient level increases monotonically as J_L increases. With respect to J_G , the large J_L series (0.8–1 m/s) shows a clear increase, particularly at medium to high J_G levels. This indicates an increase in interfacial shear and Δp_a contribution as the bubble/plug frequency rises and the film begins to thin. At a medium J_L value of 0.5 m/s, the curve shows a plateau or slight decrease in the medium J_G range, rising again in the high J_G range. This suggests a balance between shear thinning (μ_{app} decreases and friction decreases) and gas dominance (void fraction increases, plug shortens and interfacial area increases), ultimately raising the pressure gradient. At very low J_L (0.03–0.1 m/s), the pressure gradient is low, with limited sensitivity to J_G until entering the medium J_G range. This is consistent with a stable plug surrounded by a thin film, resulting in relatively low μ_{app} due to shear thinning.

Compared to CMC at 0.2% (Figure 3), all pressure gradient data were higher for every J_G - J_L combination at CMC at 0.4%. This is consistent with the greater rheological consistency at a concentration of 0.4%. The film is thicker, resulting in increased fluid holdup, so that Δp_f dominates from small J_G . However, across the entire curve, the effect of J_G on the pressure gradient appears to be gradual. At low J_L (0.03–0.1 m/s), the effect of J_G is slightly more pronounced than at a concentration of 0.2%, due to the greater initial μ_{app} .

Compared to 0.2% CMC, the pressure gradient for 0.2% XG (see Figure 4) is generally lower at the same J_L , this is particularly evident at high J_L . This is consistent with XG's stronger shear-thinning properties (smaller flow index n), meaning μ_{app} decreases more rapidly when J_G or J_L increases the

Figure 2.
Pressure gradient for
Nitrogen - 0.2% CMC
solution

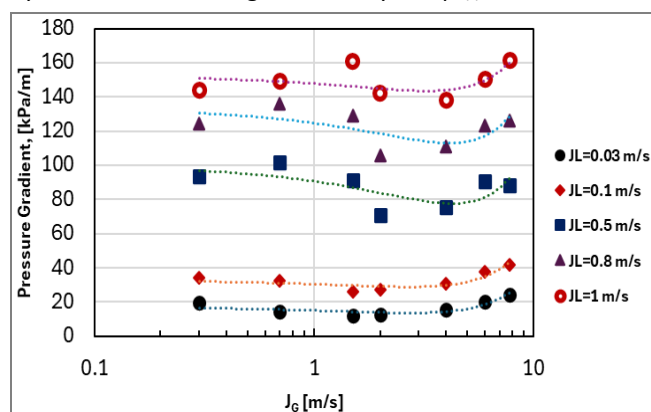


Figure 3.
Pressure gradient for
Nitrogen - 0.4% CMC
solution

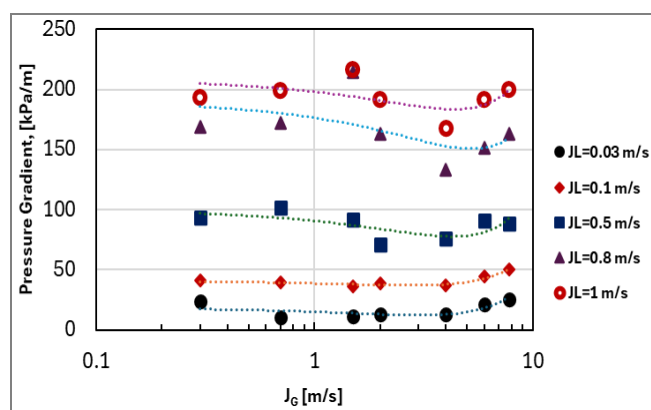


Figure 4.
Pressure gradient for
Nitrogen - 0.2% XG
solution

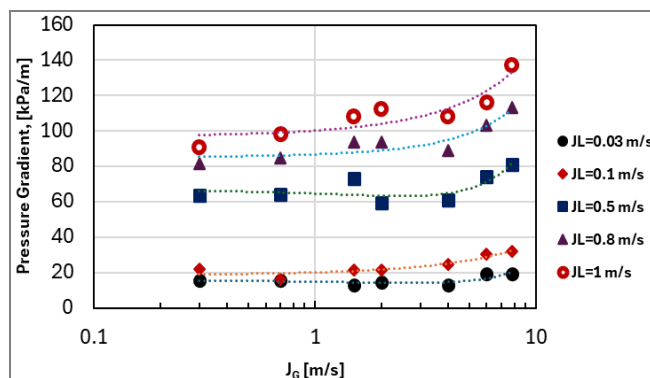
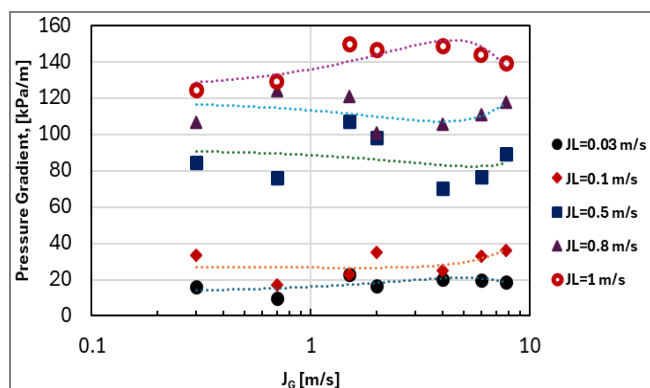


Figure 5.
Pressure gradient for
Nitrogen - 0.4% XG
solution



shear rate. The $J_L = 1$ m/s curve remains the highest. At medium J_L (0.5–0.8 m/s), the pattern of a plateau or slight increase at medium J_G , followed by an increase at high J_G , remains visible, albeit without the sharp spike seen with CMC. This indicates that the decrease in μ_{app} due to shear thinning partially compensates for the increase in interfacial shear. At very low J_L , the pressure gradient remains low, only increasing significantly at high J_G .

Figure 5 shows that increasing the XG concentration to 0.4% raises the pressure gradient in all series, but the level remains below the 0.4% CMC for the same J_L . The 1 m/s J_L series shows a systematic increase in J_G , however, at high J_G , some points begin to flatten, indicating a reduction in fluid holdup (stronger gas carry) and/or the formation of a relatively stable

gas core with an annular/slug-annular film that resists an increase in wall friction. At low J_L , the pressure gradient is almost insensitive to J_G (from low to medium) and only increases at high J_G . The shear-thinning effect on XG is stronger than on CMC, so it effectively suppresses Δp_f even at higher concentrations.

A qualitative comparison can also be made with existing mini/micro-channel studies. Yue *et al.* [28] proposed a Lockhart–Martinelli-type correlation for two-phase frictional pressure drop in a 667 μm rectangular microchannel using CO_2 water. When their correlation is evaluated for the present hydraulic diameter by using the apparent viscosity of the CMC/XG solutions as the liquid property, it reproduces the monotonic increase of $\Delta p/L$ with J_G and J_L but underestimates the measured values, particularly at the higher polymer concentrations where shear-thinning is strong. Yang *et al.* [29] reported nitrogen/non-Newtonian two-phase flow in noncircular microchannels and also observed that increasing liquid viscosity increases the frictional pressure drop. The present nitrogen–CMC/XG data are consistent with these general trends but extend them to shear-thinning liquids in a 0.8×0.8 mm horizontal square capillary and show that Newtonian-based microchannel correlations cannot fully capture the additional resistance caused by strong shear-thinning.

Therefore, in small channel designs, the two most effective ways to reduce the pressure gradient are to decrease the J_L and/or select a polymer (XG) with greater shear thinning properties at lower concentrations. J_G settings should avoid the transition zone (around the knee), as a slight increase in J_G in this region can trigger a surge in $\Delta p/L$.

3.2. Flow Pattern

An increase in J_G on J_L continues to shift the morphology from plug to slug-annular, and finally to annular. In the case of large J_L and/or a medium to high J_G , interface instability results in either bubbly spreading foam or churning (chaotic mixing flow). Due to CMC/XG shear thinning, the apparent viscosity (μ_{app}) decreases as the shear rate increases. This causes the wall film to thin at high J_G and accelerates the transition to annular flow. The difference in shear-thinning strength means that XG tends to form a 'lighter' film (lower μ_{app}) than CMC at the same concentration.

Table 3 (CMC 0.2%) shows that, at a jet velocity (J_L) of 0.03 m/s, the plug changes to a slug-annular configuration at a jet velocity (J_G) of 7.8 m/s. The appearance of a liquid neck and the formation of a film indicates that the gas is dominant, but that the film is still continuous. At a jet velocity of 1 m/s, bubbly flow ($J_G = 0.3$ m/s) changes to churn flow ($J_G = 2$ –7.8 m/s). A high liquid flow rate increases holdup. As J_G increases, coalescence and bubble breakup occur repeatedly, resulting in a 'disruption' zone, which is one of the characteristic features of churn.

Table 4 (CMC 0.4%) shows that at $J_L = 0.1$ m/s, the plug ($J_G = 0.3$ m/s) changes to slug-annular ($J_G = 6$ m/s) and then to annular ($J_G = 7.8$ m/s). An increase in concentration (0.4%) raises μ_{app} so that the film remains formed and coats the wall, enveloping the gas core. At $J_L = 1$ m/s, bubbly flow ($J_G = 0.3$ m/s) changes to churn ($J_G = 4$ and 7.8 m/s).

For $X_G = 0.2\%$ (**Table 5**), at $J_L = 0.1$ m/s it is a plug flow ($J_G = 0.3$ and 4 m/s) and then a slug-annular flow ($J_G = 7.8$ m/s). At $J_L = 1$ m/s, the bubbly flow ($J_G = 0.3$ m/s) changes to churn ($J_G = 4$ to 7.8 m/s) with a visible disruption area. However, the pattern is less 'rough' than CMC because μ_{app} XG decreases more strongly at high J_G .

Table 3.
Flow patterns observed
in two-phase flow
nitrogen-0.2% CMC
solution

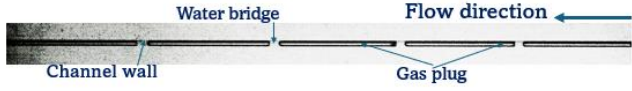
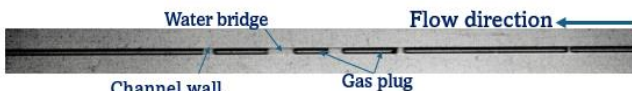
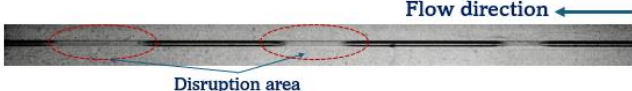
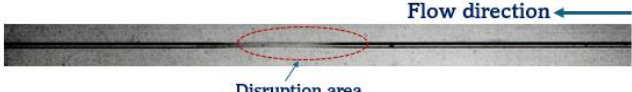
No	J_L [m/s]	J_G [m/s]	Flow Configuration	Flow pattern
1	0.03	0.3		Plug
2	0.03	2		Plug
3	0.03	7.8		Slug-annular
4	1	0.3		Bubbly
5	1	2		Churn
6	1	7.8		Churn

Table 4.
Flow patterns observed
in two-phase flow
nitrogen-0.4% CMC
solution

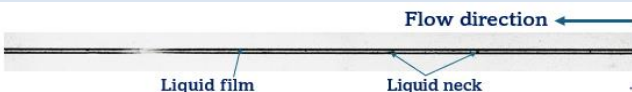
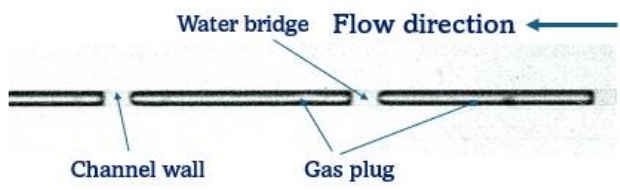
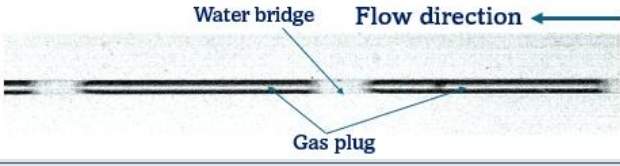
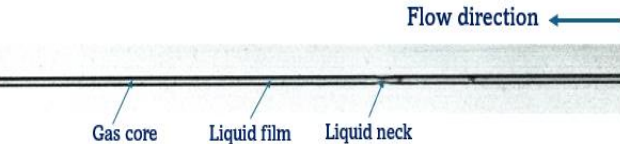
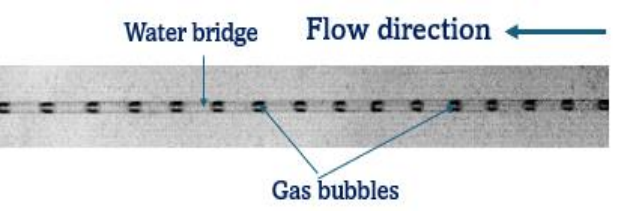
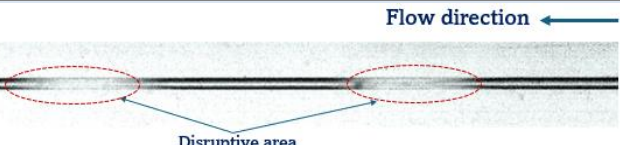
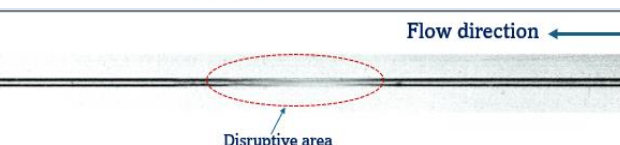
No	J_L [m/s]	J_G [m/s]	Flow Configuration	Flow pattern
1	0.1	0.3		Plug
2	0.1	6		Slug-annular
3	0.1	7.8		Annular
4	1	0.3		Bubbly
5	1	4		Churn
6	1	7.8		Churn

Table 5.
Flow patterns observed
in two-phase flow
nitrogen-0.2% XG
solution

No	J_L [m/s]	J_G [m/s]	Flow Configuration	Flow pattern
1	0.1	0.3		Plug
2	0.1	4		Plug
3	0.1	7.8		Slug-annular
4	1	0.3		Bubbly
5	1	4		Churn
6	1	7.8		Churn

In **Table 6** (XG 0.4%), at $J_L = 0.1$ m/s, the flow changes from plug ($J_G = 0.3$ m/s) to slug-annular ($J_G = 4$ m/s), and then to annular ($J_G = 7.8$ m/s). This is similar to CMC 0.4%, but the film appears thinner and the gas core is cleaner. At $J_L = 1$ m/s, bubbly flow ($J_G = 0.3$ m/s) changes to churn flow ($J_G = 4$ and 7.8 m/s). Although the flow pattern is churn, the interface disturbance is less sharp than that of CMC (indicating a lower μ_{app} at high shear rates). In terms of hydrogen transport, churns are the least desirable due to pressure oscillations and irregularities in the gas/electrolyte supply.

Table 3 to **Table 6** shows a consistent transition map. J_G shifts towards annular flow, while high J_L leads to bubbly flow and churning. Shear-thinning strength ($XG > CMC$) smooths the interface and suppresses oscillations. To optimize hydrogen transport, the operating domain should avoid churn/slugging and select a J_G - J_L combination that produces bubbly, plug, slug-annular and stable annular flows, in accordance with water management requirements and system pressure loss limits.

3.3. Flow Pattern Map

Figure 6 to **Figure 9** show a flow pattern map summarizing the two-phase dynamics of nitrogen–non-Newtonian solutions (CMC and XG) in a horizontal 0.8×0.8 mm square capillary tube. The horizontal axis represents the superficial gas velocity (J_G) and the vertical axis represents the liquid superficial velocity (J_L). Each symbol marks a visually observed regime: bubbly, plug, slug-annular, annular and churn. The drawn boundary lines represent transition thresholds. Due to the horizontal channel, hydrostatic contributions can be neglected. Regime shifts are primarily determined by the balance between interfacial shear and void fraction, which increase with J_G , and holdup and the liquid's apparent viscosity, which increase with J_L . A distinctive feature of this system is the shear-thinning, non-Newtonian liquid. When the shear rate increases (due to either

J_G or J_L increasing), μ_{app} decreases. The competition between this decreases and the increase in interfacial forces shapes the map topology.

At 0.2% CMC (see Figure 6), the plug region dominates at a medium J_L and a low J_G , up to approximately 1 m/s. The gas column is segmented by a 'water bridge' at the corner of the channel, a thin film of liquid and a stable slug extending along the channel. When J_G is increased at high J_L (approximately 0.8–1.0 m/s), the regime immediately shifts towards churning. Bubble breakage occurs repeatedly, the interface becomes chaotic, and the disruption region spreads along the channel. Conversely, at low J_L (≤ 0.1 m/s) and sufficiently large J_G (4–8 m/s), the gas core elongates, and the wall film becomes more continuous, shifting the pattern to slug-annular. In other words, J_G shifts the system towards gas dominance (an elongated core and a continuous film), while high J_L drives the system towards bubbly flow and then churn through increased holdup and μ_{app} .

Increasing the CMC concentration to 0.4% (Figure 7) resulted in a narrower churn area. This indicates that the churn flow pattern was more difficult to form due to the higher viscosity, which prevented turbulence from occurring. For low J_L , an annular regime was observed at J_G of around 7.8 m/s. The wall film was relatively continuous, while the gas core remained clean. Physically, this map reflects two mechanisms operating simultaneously: higher μ_{app} increasing holdup, and shear-thinning continuing to thin the film so that an annular regime can form at low J_L .

For XG at 0.2% (Figure 8), the map topology resembles that of CMC at 0.2%, but with a smooth shift that is consistent with the stronger shear-thinning of the XG. At a combination of high J_L and medium J_G , churn still occurs, but the threshold is slightly to the right (requiring a higher J_G), and the churn range is narrower. At low J_L and high J_G , the system tends to persist slightly longer in the slug-annular state before transitioning to full annular flow. This indicates that the decrease in XG μ_{app} at high shear rates is sufficient to 'tame' some of the instability. Although increased interfacial forces still raise the void fraction, wall friction decreases, resulting in a smoother transition.

Table 6.
Flow patterns observed
in two-phase flow
nitrogen-0.4% XG
solution

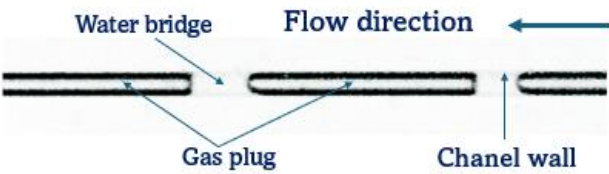
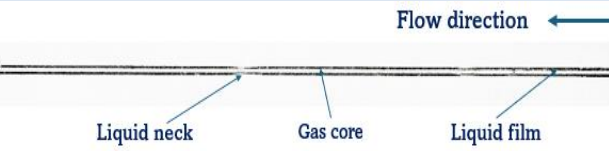
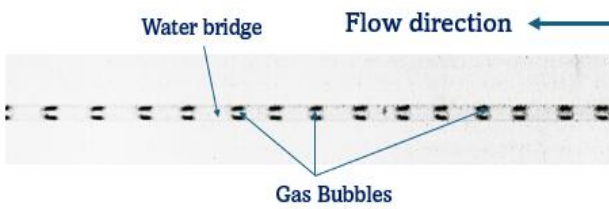
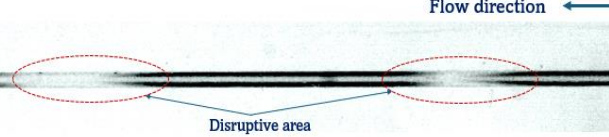
No	J_L [m/s]	J_G [m/s]	Flow Configuration	Flow pattern
1	0.1	0.3		Plug
2	0.1	4		Slug-annular
3	0.1	7.8		Annular
4	1	0.3		Bubbly
5	1	4		Churn
6	1	7.8		Churn

Figure 6.
Flow pattern map for
Nitrogen - 0.2% CMC
solution

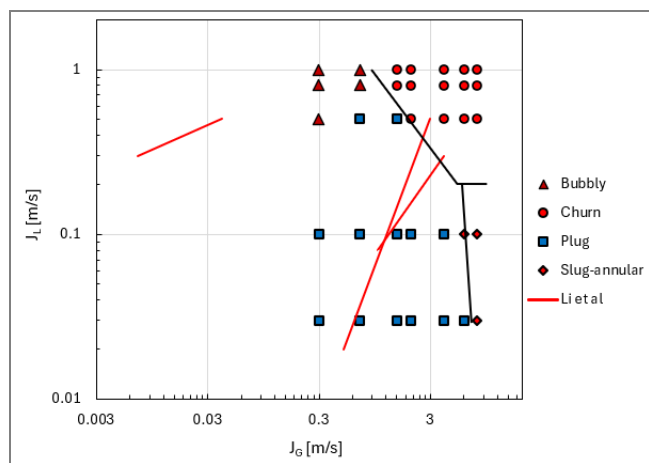


Figure 7.
Flow pattern map for
Nitrogen - 0.4% CMC
solution

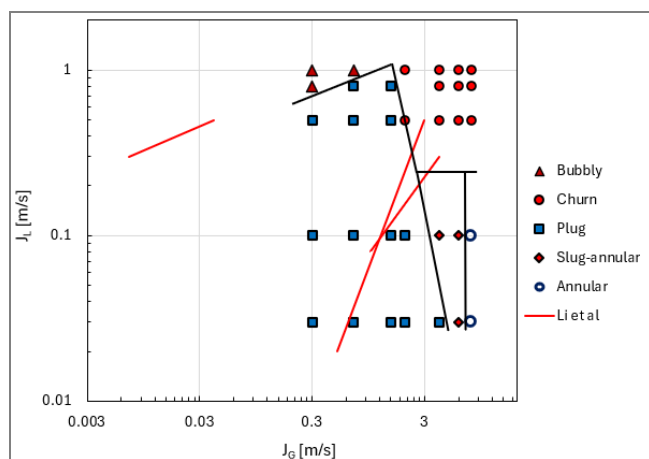


Figure 8.
Flow pattern map for
Nitrogen - 0.2% XG
solution

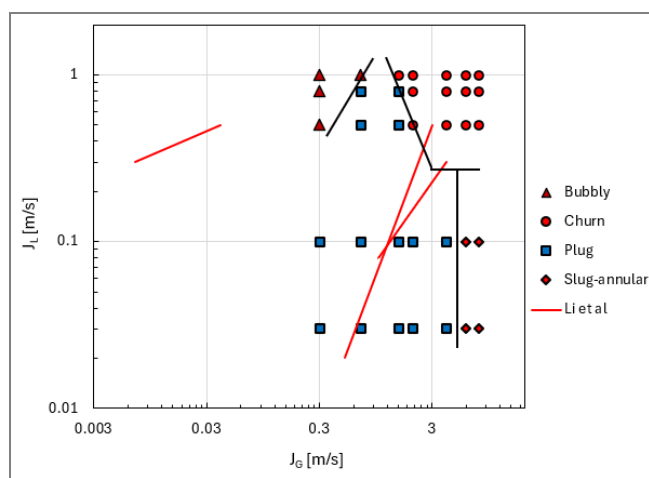


Figure 9.
Flow pattern map for
Nitrogen - 0.4% XG
solution

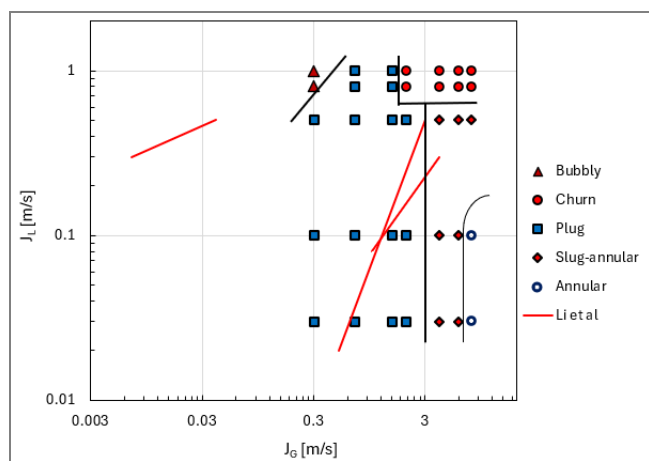


Figure 9 (XG 0.4%) supports this conclusion. While the increase in concentration raises the base viscosity level and narrows the churn area at high J_L , compared to CMC 0.4%, the churn area remains almost unchanged. At low J_L , the transition from slug-annular to annular flow occurs. In other words, at the same concentration, XG provides a more 'user-friendly' map than CMC. Churn is more controlled, with annular formation occurring without sharp spikes in turbulence.

The direction of boundary shift seen in this map is consistent with the trends reported by Sudarja *et al.* [22] in small pipes or capillaries (generally involving Newtonian fluids or water-glycerin mixtures with circular geometry, partly in inclined pipes). Their results show that an increase in fluid viscosity and flow rate increases holdup, raising the pressure gradient. Meanwhile, gas dominance at high J_G drives flow towards the annulus. While the channel here is square and the fluid is non-Newtonian, the two signs identified by Sudarja *et al.* [21] (the effect of viscosity on the churn area and the appearance of the annulus at high J_G when J_L is small) also appear in this study's map. One notable difference is the effect of non-Newtonian. At XG, shear-thinning that is stronger than the CMC shifts the plug/churn threshold to a larger J_G . This is not captured by conventional Newtonian correlations.

The present maps can also be compared with the nitrogen/non-Newtonian microchannel study of Yang *et al.* [29], who examined 0.4% CMC, 0.2% PAM and 0.2% XG solutions in vertical noncircular microchannels with hydraulic diameters between about 0.9 and 2.9 mm. They observed slug, churn and annular regimes and reported that increasing the liquid viscosity increases the frictional pressure drop and modifies the extent of the churn region, while the channel hydraulic diameter and cross-section shape also influence regime

transitions. In this horizontal 0.8×0.8 mm square channel, the overall topology of the J_G – J_L maps is similar, but increasing polymer concentration from 0.2% to 0.4% narrows the churn domain, and the strongly shear-thinning XG solutions yield a more stable map than CMC at the same concentration. These differences suggest that the combined effects of shear-thinning, channel size and horizontal orientation modify how viscosity influences churn flow, and they complement Yang's vertical-flow data by providing a contrasting non-Newtonian database for small horizontal square channels.

A qualitative comparison can also be made with the non-Newtonian Taylor bubble study of Li [30], who investigated air–CMC flow in a 150×50 μm rectangular T-microchannel using water and several CMC solutions. For this purpose, Li's regime boundaries are superimposed on the present J_G – J_L map for reference. Although the channel size, geometry and CMC concentration range differ from those in the present work, both studies highlight that enhancing viscosity and shear-thinning tends to expand the Taylor/slug region, shift the transition towards annular- or churn-like regimes to higher gas superficial velocities, and reduce the extent of highly disturbed flow. These similarities indicate that the topology and trends of the present J_G – J_L flow pattern maps are consistent with earlier non-Newtonian Taylor flow studies, while extending them to higher polymer concentrations and a square microchannel geometry.

From a dimensionless point of view, replacing nitrogen with hydrogen mainly affects gas-side groups such as the Reynolds number, Weber number, and the capillary number. For the same channel size and superficial gas velocity, hydrogen has a much lower density and a slightly lower viscosity than nitrogen. As a result, the corresponding Re and We values change and the balance between gas inertia and surface tension is modified, especially in annular and churn-like regimes. However, the basic mechanisms that control the transitions between plug, slug-annular, annular and churn remain the same, namely the interplay between gas inertia, interfacial tension and the shear-thinning behaviour of the liquid. Therefore, although the exact numerical positions of the regime boundaries in the J_G versus J_L plane will differ for hydrogen, the qualitative topology of the maps and the comparative trends observed between CMC and XG solutions are expected to remain valid for hydrogen–liquid systems in similar small channels.

A direct practical implication for hydrogen transport can be drawn. In gas distribution channels in PEM fuel cells or electrolyzers, a bubbly/plug regime at low J_G can help maintain humidity and avoid local drying. Since hydrogen has a lower density and viscosity than nitrogen, the gas-liquid slip is greater at the same J_G . This means that annular flow tends to appear earlier (the map shifts 'to the left' on the J_G axis) when these results are applied to H_2 systems. Therefore, in practice, J_G – J_L pairs should be selected to target stable bubbly/plug flow for humidification strategies, or stable annular flow when rapid water removal is a priority, while avoiding churn. If the system requires an additive liquid, selecting a polymer that exhibits greater shear thinning (analogous to XG here) or reducing its concentration will help to narrow the churn domain and lower the pressure 'cost'.

Overall, Figure 6 to Figure 9 show flow pattern maps that are consistent with the theoretical framework and align with trends reported in previous capillary experiments. J_L regulates the holdup level, J_G controls gas core elongation and transition, and viscosity narrows churn, though strong shear-thinning stabilizes the interface. These findings provide a robust foundation for determining the operating limits of two-phase flow in small square channels, supporting both fundamental research and the design of safe, efficient, and oscillation-resistant in hydrogen transport systems.

3.4. Pressure Gradient Time Series and PSD Analysis

In general, J_L increases the base level of the pressure gradient ($\Delta p/L$) by increasing holdup and wall friction. Meanwhile, J_G regulates interface morphology and triggers regime transitions. Stable regimes (plug/slug-annular) exhibit more regular oscillations with smaller standard deviations in time series. In contrast, churn exhibits irregular fluctuations with large standard deviations. In power spectral density (PSD), the periodic regime is characterized by a dominant frequency peak (fp) and a narrow bandwidth. Unstable regimes (churn) exhibit broadband, with energy expanding to higher frequency bands. The difference between CMC and XG (0.2 and 0.4%) modulates the intensity of the phenomenon. Increasing concentration increases ($\Delta p/L$) and accelerates the onset of churn. Meanwhile, XG (with greater shear thinning) generally exhibits more damped fluctuations and a more ordered spectral band at the same set point.

Table 7 shows that, at 0.2% CMC ($J_L = 0.03$, $J_G = 0.3$), the $\Delta p/L$ time series shows small- to medium-periodic ripples that are coherent and indicative of plugging with fluid bridges at the

channel corners. The power spectral density (PSD) displays a single sharp peak at low to mid-frequency (slugging frequency), a narrow bandwidth and a high band-power ratio (the power of the peak band compared to the power of the other bands). Increasing the CMC to 0.4% ($J_L = 0.1$, $J_G = 0.3$) increases ($\Delta p/L$) (higher rheological consistency) and slightly broadens the PSD peak (increased fluctuation energy), but the primary periodicity is maintained. At XG 0.2 and 0.4% ($J_L = 0.1$, $J_G = 0.3$) and due to stronger shear thinning of XG, μ_{app} decreases faster at high shear rates, resulting in a narrower oscillation amplitude and bandwidth in the PSD than in the CMC. However, the peak frequency (f_p) remains clear. In conclusion, the plug is characterized by a narrow, dominant PSD peak and a low-to-medium STD of $\Delta p/L$, with ($\Delta p/L$) increasing as the concentration increases.

As illustrated in Table 8, with $J_L = 1$ m/s, small bubbles are denser and interface interactions are more frequent, but J_G remains low. At CMC 0.2 and 0.4% ($J_G = 0.3$), the mean pressure gradient ($\Delta p/L$) increases sharply compared to the plug state (due to holdup and wall friction). The time series exhibits noisier, but not yet chaotic, oscillations and the power spectral density (PSD) show a broader peak with weaker sidebands, indicating weakened periodicity due to less synchronous bubble interactions. At XG 0.2 and 0.4%, the shear-thinning effect makes the fluctuation amplitude more controlled. The PSD still shows a main peak, but the high-frequency energy is smaller than at CMC at the same concentration. In general, bubbly displays a broadened PSD peak with a high ($\Delta p/L$).

Table 7.
PSD for plug flow

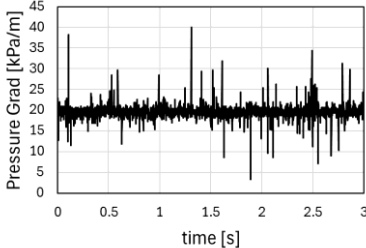
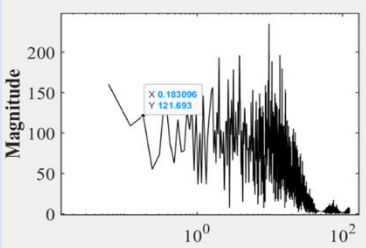
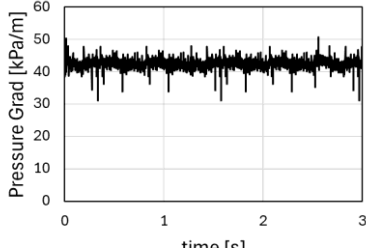
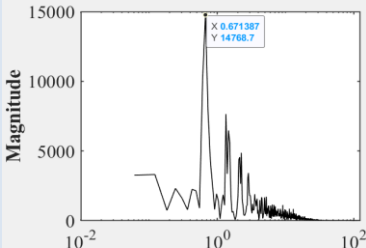
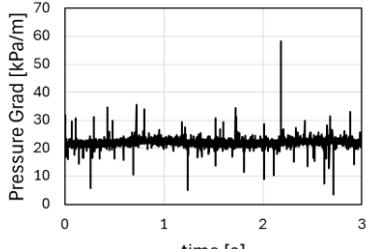
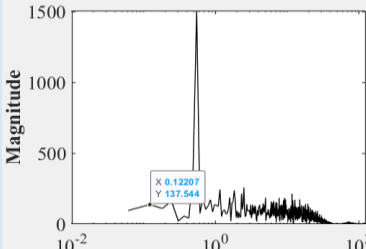
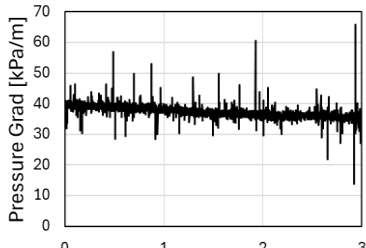
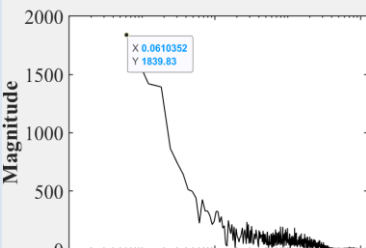
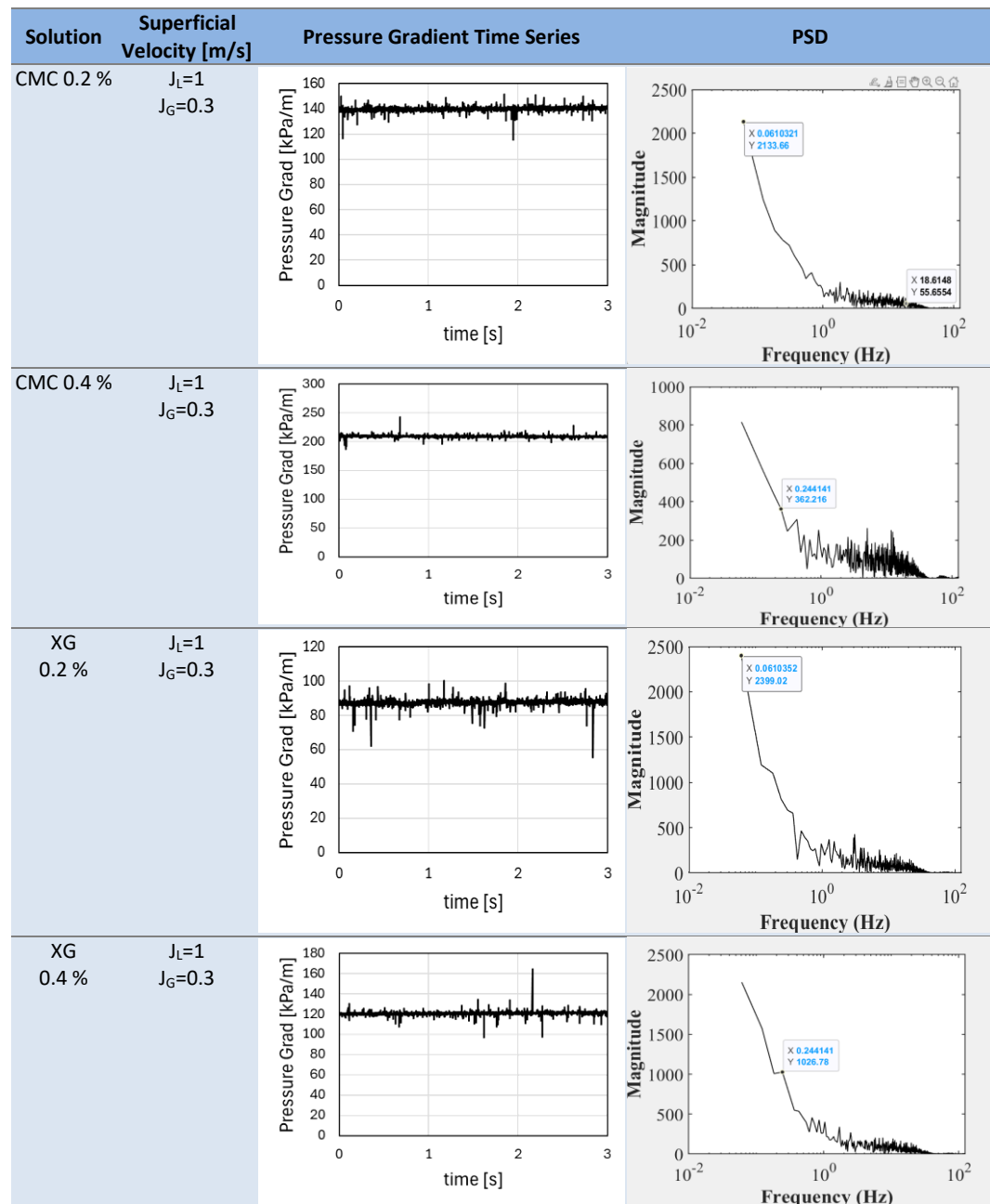
Solution	Superficial Velocity [m/s]	Pressure Gradient Time Series	PSD
CMC 0.2 %	$J_L=0.03$ $J_G=0.3$		
CMC 0.4 %	$J_L=0.1$ $J_G=0.3$		
XG 0.2 %	$J_L=0.1$ $J_G=0.3$		
XG 0.4 %	$J_L=0.1$ $J_G=0.3$		

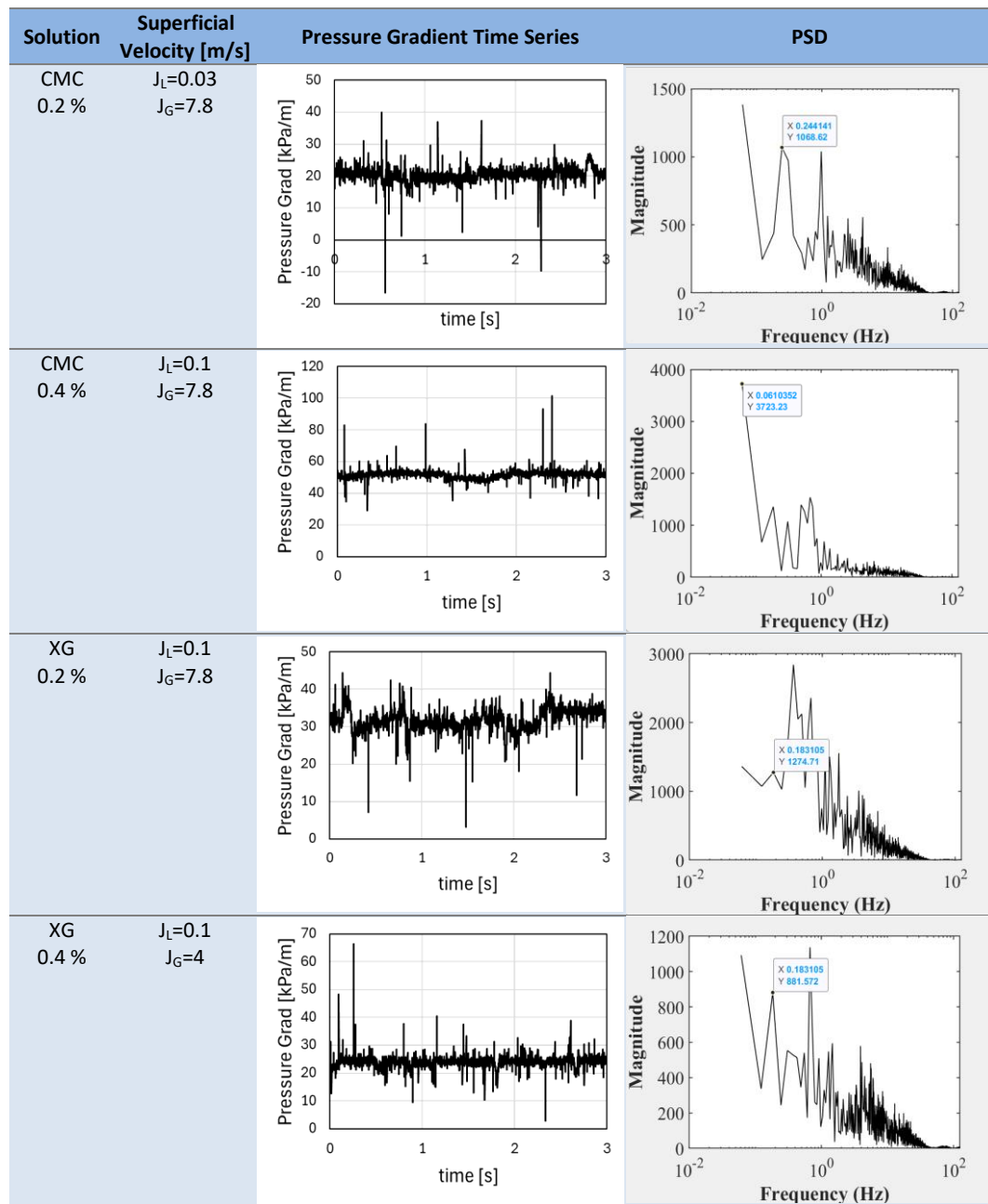
Table 8.
PSD for bubbly flow



As shown in [Table 9](#), the transition to slug-annular flow occurs at CMC concentrations of 0.2% ($J_L = 0.03$, $J_G = 7.8$) and 0.4% ($J_L = 0.1$, $J_G = 7.8$), and is characterized by an elongated gas core and a relatively continuous wall film. $\Delta p/L$ increases compared to the low J_G regime, but STD $\Delta p/L$ decreases relative to churn (see [Table 8](#)) because dynamics are dominated by film waves rather than random coalescence-breakup. At PSD, the slugging peak weakens while the mid-to-high energy band (film waves) becomes more prominent. This results in a spectrum with shallower peaks or narrow multi-bands. At XG 0.2% ($J_L = 0.1$, $J_G = 7.8$), the spectrum tends to be neat (the high bands are present, but not bursting), whereas at XG 0.4% ($J_L = 0.1$, $J_G = 4$), annular/slug-annular formation occurs at a lower J_G than the CMC. This is consistent with a faster decrease in μ_{app} at high shear rates, which makes it easier to stabilize the gas core. The key feature of the slug-annular state is that the PSD energy shifts towards the mid-high band (film waves).

As shown in [Table 10](#), the combination of $J_G = 7.8$ and $J_L = 1$ (for all solutions) activates the most unstable regime, churn. The $\Delta p/L$ time series exhibits large, intermittent and irregular fluctuations. In PSD, the energy broadens and the bandwidth increases significantly. The spectral centroid also shifts to higher frequencies, indicating a chaotic interface spectrum. Compared to CMC, XG (at 0.2% and 0.4%) generally exhibits slightly more damped high-band energy and more moderate STD $\Delta p/L$. This indicates the effect of shear thinning in 'taming' churn at the same set point.

Table 9.
PSD for slug-annular flow

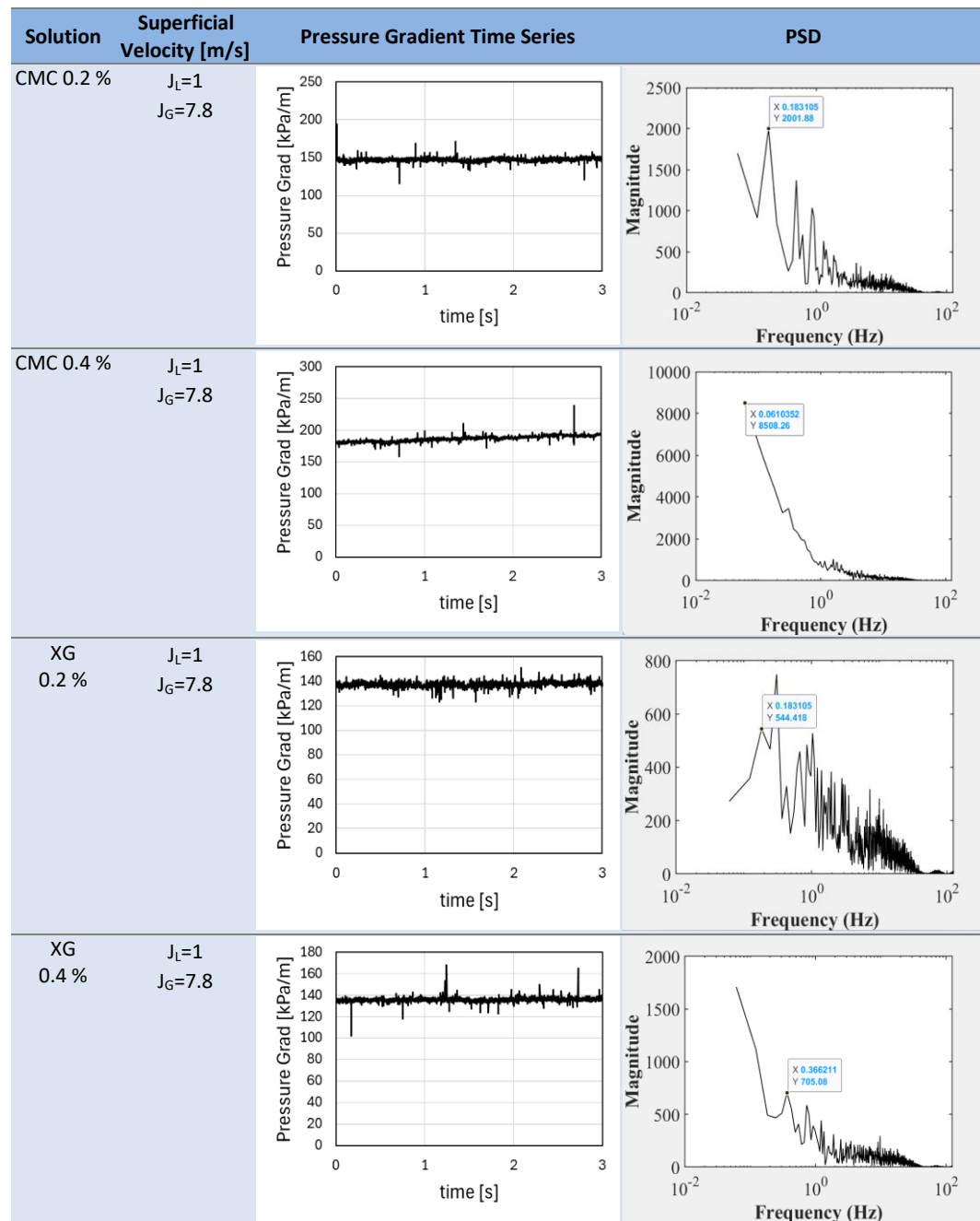


4. Conclusions

Research has been conducted on the two-phase flow characteristics of nitrogen-CMC and nitrogen-XG solutions in 0.8 mm x 0.8 mm square capillary tubes, and the results and analysis are described. The following conclusions can be drawn from the above description:

- In general, J_L primarily controls the base level of the pressure gradient, while J_G triggers a further increase, particularly after entering the transition zone. In all solutions, $\Delta p/L$ increases monotonically with J_L due to increased holdup and wall friction. Increasing the concentration from 0.2% to 0.4% for both CMC and XG increases rheological consistency, resulting in a higher pressure gradient in all J_G - J_L combinations and an earlier appearance of the knee. Compared to CMC, XG exhibits stronger shear thinning, consequently, μ_{app} decreases more rapidly at high shear rates, resulting in a generally lower pressure gradient for XG than for CMC at the same concentration and set point.
- The image sequence shows coherent morphological evolution. At low J_L and low J_G , plug flow (or bubbly flow at high J_L) is characterized by the intermittent appearance of bubbles or plugs with water bridges. Increasing J_G elongates the gas core and thins the wall film, shifting the pattern to slug-annular, and at high J_G and low J_L to annular with a clean gas core. Conversely, at high J_L , increasing J_G triggers the formation of disruptive areas, creating chaos and a churn flow pattern.

Table 10.
PSD for churn flow



- c. The flow pattern maps show that an increase in concentration from 0.2% to 0.4% (for both CMC and XG) shifts the plug-churn boundary to a higher J_G at high J_L . This narrows the churn domain. At low J_L , however, the increase in concentration facilitates annular formation when the J_G value is high. Compared to the CMC map, the XG map shows a narrower churn region and a threshold that is slightly further to the right (requiring a higher J_G). In terms of application, the maps clearly show an operational J_G - J_L pair. Bubbly/plug-stable at a low J_G is suitable for maintaining humidity but requires control of flooding. Annular-stable at a high J_G with a low J_L is effective for water removal, resulting in a larger pressure gradient. The churn flow pattern should be avoided because it induces pressure oscillations. For hydrogen transport, since H_2 is lighter and has a lower viscosity than N_2 , the boundary towards annular flow will shift towards a smaller J_G . Therefore, selecting the appropriate J_G - J_L combination and rheology (e.g. using a more shear-thinning fluid such as XG or reducing concentration) is key to suppressing pressure losses and avoiding instability in the small channels and manifolds of the hydrogen system.

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sub-contracts no. 0498.07/LL5-INT/AL.04/2025, and 38/KP-DRP-RISET/VI/2025. The author would also like to thank the Directorate of Research and Community Service (DRP) at Universitas Muhammadiyah Yogyakarta (UMY) for their guidance, and all members of the UMY two-phase flow research group for their support.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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