TRANSITION FROM LAMINAR TO TURBULENT FLOW IN NON-NEWTONIAN CHANNEL
FLOWS: THE IMPACT OF DRAG REDUCING POLYMER ADDITIVES
by

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Abstract

This thesis investigates the effect of a drag-reducing polymer on laminar-turbulent transition in a gravity-driven channel flow. The drag-reducing polymer is polyacrylamide (PAM) dissolved in water at concentrations of 50, 75, 100, and 150 parts per million (ppm). An extensive experimental campaign utilizing particle image velocimetry is conducted to measure the velocity field in streamwise-wall-normal and streamwise-spanwise planes across a range of Reynolds numbers (Re). The transition to turbulence is delayed by the introduction of PAM, with the delay increasing with the relaxation time of the polymer solution.

For low PAM concentrations of 50 and 75 ppm, the skin friction coefficient (C_f) increases with increasing Re before the onset of drag reduction around $Re = 2500$. After the drag reduction onset, C_f values will decline with further increase in Re. The transitional flow structures in the streamwise-wall-normal plane resemble Newtonian turbulence, containing recognizable turbulent spots. In the streamwise-spanwise plane, the turbulent core appears connected to chaotic streaks attached to the leading edge of the spot.

In contrast, the higher PAM concentrations of 100 and 150 ppm display substantially different transitional physics. The C_f values depart the laminar trend at $Re \approx 3000$, approaching the maximum drag reduction asymptote without demonstrating an onset point. The solutions undergo a remarkably smoother transition spanning over a Re range of approximately 1000 units. Turbulent spots are minimal, and elongated streamwise streaks dominate the flows instead.

Analysis of turbulence statistics reveals concentration-dependent modifications. At 50 and 75 ppm, turbulence intensity matches the Newtonian value of around 1% in laminar regions between turbulent spots. However, at 100 and 150 ppm, the intensity grows to 1.7% in laminar regions, indicating enhanced fluctuations. Within turbulent regions, intensity declines from 5% in Newtonian cases to 3% at 150 ppm, suggesting substantial turbulence attenuation.

In summary, this thesis demonstrates the impact of polymer additives on transitional channel flows. The additives expand the transitional regime and transform the emergence of coherent structures in a concentration-dependent manner, as evidenced by elongated streaks dominating at higher concentrations.

Preface

The research, experiments and analysis described in this thesis were carried out by me under the supervision of Dr. Sina Ghaemi in the Department of Mechanical Engineering at the University of Alberta. The results from this study are currently being prepared for submission to a peer-reviewed journal. I have written the entirety of both this thesis document and the manuscript under the guidance of my supervisor. In this document, the content and structure conform to the requirements for a thesis while retaining the core ideas and results from my research work which will appear in further publications.

Acknowledgments

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1. Introduction

1.1 Motivation

Turbulent flows are ubiquitous in nature and engineering applications, from ocean currents to airplane wings. Turbulence arises from instabilities in laminar flows as the Reynolds number (Re) increases past a critical point, initiating a transition to chaotic and irregular motion. This laminar-turbulent transition process is complex and a longstanding topic of fluid mechanics research dating back to the pioneering work of Reynolds (1883). While much progress has been made, gaps remain in understanding key aspects of the transition physics.

In wall-bounded shear flows like pipes and channels, the transition is characterized by localized turbulent regions (spots, streaks, puffs) emerging within the laminar flow. The gradual proliferation and merging of these coherent structures ultimately leads to fully turbulent flow (Corrsin 1943; Emmons 1951; Wygnanski & Champagne 1973).

However, the specific transitional structures and evolution pathway varies for different flow geometries and fluids.

Significant complications arise when viscoelastic polymer additives are introduced typically for drag-reduction applications. Even trace amounts of flexible polymers can dramatically alter the transition process and turbulence dynamics through elastic turbulence mechanisms. Polymers are observed to delay and smooth the transition, expand the transitional regime over a wider Reynolds number range, and modify the coherent structures that emerge (Virk 1975; White & Mungal 2008). Yet many open questions persist regarding polymer effects on transitional flows.

Advancing the fundamental knowledge in this area will aid the optimization of polymeric drag reduction and efforts to control turbulence for energy savings. Furthermore, non-Newtonian fluids are widely encountered in applications, so improved transition understanding is invaluable for predicting behaviour in industrial flows. Therefore, extensive research focused explicitly on mapping polymer impacts on transitional statistics, critical parameters, coherent structures, and flow morphology is imperative.

The primary objective of this thesis is to elucidate the effects of polymer additives on the transitional flow physics of rectangular channel flows. While prior studies have explored polymer impacts in pipe geometries, little is known about how dilute polymer solutions modify the emergence of coherence structures and evolution of turbulence statistics during transition in channel flows. This work aims to address this knowledge gap through extensive PIV measurements and analysis of critical

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parameters. The outcomes are expected to provide new insights into polymer transition delay mechanisms and differences compared to Newtonian fluid behavior in canonical channel flows.

1.2 Thesis Overview

This thesis systematically investigates the influence of polymer additives on laminar-turbulent transition in rectangular channel flows. The fluids examined include a Newtonian solvent and dilute solutions of a flexible polymer, polyacrylamide (PAM), at various concentrations. The study utilizes time-resolved particle image velocimetry to quantify flow statistics and visualize transitional flow fields in streamwise wall-normal and spanwise planes.

The thesis is structured as follows: Chapter 2 reviews relevant literature on transitional flows and polymer effects. Chapter 3 details the experimental methods. Chapter 4 presents results for the Newtonian fluid and polymer solutions. The evolution of skin friction, turbulence fraction, velocity profiles, and flow morphology are analyzed across a range of Reynolds numbers spanning laminar, transitional, and turbulent regimes. Chapter 5 discusses the key findings regarding polymer impacts on the transitional statistics, critical parameters, coherence structures, and flow fields compared to the Newtonian fluid. Finally, Chapter 6 summarizes the conclusions.

2. Literature Review

2.1 Laminar-Turbulent Transition in Newtonian Flows

The study of laminar to turbulent flow transition in shear flows has been a prominent area of research within fluid mechanics, originating from Reynolds's (1883) groundbreaking experiment. Since then, a substantial body of literature has emerged, delving into the instability and laminar-turbulent transition in shear flows, with numerous publications contributing to the evolving comprehension of this phenomenon (Eckhardt *et al.* 1998; Manneville 2016). The broad applicability of wall-bounded flows has accentuated the significance of identifying the "critical Reynolds number" at which this transition occurs.

This literature review commences with an introduction to transitional flow structures, accompanied by a succinct summary of their key attributes. Following this, a brief exploration of various approaches for determining the critical Reynolds number in pipe and channel flows is presented.

2.1.1 Coherent Structures in Transition

At the initial stage of turbulence, localized regions of turbulent flow are encircled by laminar flow. These flow formations, known as coherent structures, are integral to the transition process. The shift from laminar to turbulent flow is contingent upon the growth or decay of these coherent structures.

Coherent structures were first identified during the transition process in a boundary-layer flow and were designated as "Turbulent Spots" by Emmons (1951). However, the recognition of various structures has been found to be dependent on factors such as the type of flow, Reynolds number, and the level of disturbance.

2.1.1.1 Pipe Flows:

In the 1970s, the concept of coherent structures in pipe flow was first seriously discussed, beginning with Wygnanski and Champagne's (1973) experimental study on transitional pipe flows. They conducted hot-wire measurements in a smooth air pipe with a diameter of 3.3 cm, covering a Re range of 1,000 to 100,000. Their research identified two distinct transitional structures: "slugs" and "puffs."

Slugs are observed at high Re values and are caused by minor disturbances in the pipe's inlet region. In contrast, puffs are generated by significant disturbances at the inlet and can appear at relatively lower Re values. According to Wygnanski and Champagne (1973), the flow within a slug closely resembles the fully developed turbulent flow. Slugs exhibit well-defined interfaces, termed "Leading Edge" and "Trailing Edge," between the turbulent flow inside and the surrounding laminar flow.

As slugs grow, they can occupy a significant portion of the pipe, resulting in a fully turbulent pipe flow.

In the subsequent years, Wygnanski and colleagues (1975) expanded their research to investigate puffs. The experimental setup was modified to incorporate a speaker on the funnel to generate disturbances. The study was carried out within a *Re* range of 2,000 to 3,500. The researchers found that the length of the puff is dependent on the *Re*, with all puffs at the same *Re* having equal lengths. Moreover, as the flow moves downstream towards the puff's rear, the turbulent intensity gradually increases, reaching its maximum at the trailing edge. However, the researchers were unable to identify a distinct interface between turbulent and non-turbulent regions near a puff's leading edge. Further analysis showed that a puff travels at a velocity approximately equal to the pipe's spatial average velocity.

Avila *et al.* (2011) conducted a thorough investigation of puffs in transitional pipe flow, utilizing both experimental and numerical analysis techniques. The researchers selected a pipe diameter of 4 mm and introduced impulsive perturbation to the fully developed laminar flow using a water jet. To experimentally identify and track a puff, pressure was measured at two downstream locations. The acquisition of pressure signals enabled them to determine whether the turbulent fraction of the flow increased, remained constant, or decreased during downstream propagation.

In their numerical analysis, Avila *et al.* (2011) employed direct numerical simulations (DNS) and investigated *Re* ranging from 2,032 to 2,385. The numerical simulations corroborated previous observations regarding the leading edge and

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trailing edge interfaces of a puff. Avila *et al.* (2011) noted that the upstream boundary of a puff is well-defined, while the downstream boundary is less distinct. They further explained that the increase in turbulence arises from the spatial proliferation of turbulent patches, rather than the temporal complexity of fluid motion. This spatial proliferation was termed "puff splitting." When a puff extends in length to the point where vorticity decays in its central streamwise region, a vorticity patch escapes from the primary puff and forms a new puff. As mentioned earlier, slugs grow in size, while puffs primarily increase in number. Consequently, spatial proliferation serves as another distinguishing factor between puffs and slugs.

Barkley *et al.* (2015) utilized a combination of experimental, theoretical, and computational methods to study the emergence of fully turbulent flow in pipes and ducts. The pipe had a diameter of 10 mm, while the duct had a width of 5 mm. The disturbance generation technique and pressure sensing equipment were similar to those employed by Avila *et al.* (2011). However, for the duct experiments, five pressure sensors were placed at various downstream points. Barkley and colleagues (2015) demonstrated that in both pipe and duct flows, the velocity of the downstream front of a turbulent patch is indistinguishable from the upstream front, indicating localized turbulence at the onset. For pipe flow with $Re \gtrsim 2,250$ and duct flow with $Re \gtrsim 2,030$, the speed of the downstream front increases with the Re. These values represent the threshold at which turbulence begins to aggressively invade the surrounding laminar fluid.

2.1.1.2 Channel Flows:

The visualization of turbulent spots in channel flow has been the subject of early experimental investigations by Carlson *et al.* (1982) and Alavyoon *et al.* (1986). It is worth noting that channel flow and plane Poiseuille flow (PPf) are often treated as the same type of flow in literature due to their similarities. Interestingly, both channel flow and PPf studies are conducted in channel facilities, but PPf studies aim to use channels with higher aspect ratios (the ratio of width to height in channel cross-section) to simulate the infinite plane assumption of Poiseuille flow.

In their study, Carlson *et al.* (1982) investigated the visualization of turbulent spots in plane Poiseuille flow by artificially triggering a transition. To achieve this, they used titanium dioxide-coated mica particles for flow visualization inside a water channel with an aspect ratio of 133. The flow was disturbed by an electromagnetic solenoid, and the resulting turbulent spot is shown in Figure 2.1. The turbulent spot in channel flow has an arrowhead shape, with oblique waves visible at the sides and rear of the spot, as observed by Carlson *et al.* (1982). They also noted that as the turbulent spot travels downstream, it becomes more spread out (primarily in the spanwise direction) until it eventually divides into two separate turbulent spots at sufficiently large *Re*. The oblique waves around the turbulent spot resemble those observed in boundary layer flows, but the splitting of coherent structures has not been reported in boundary layers. This is likely due to the bounded geometry of transitional channel flow, which results in an energy transfer mechanism more similar to pipe flow.

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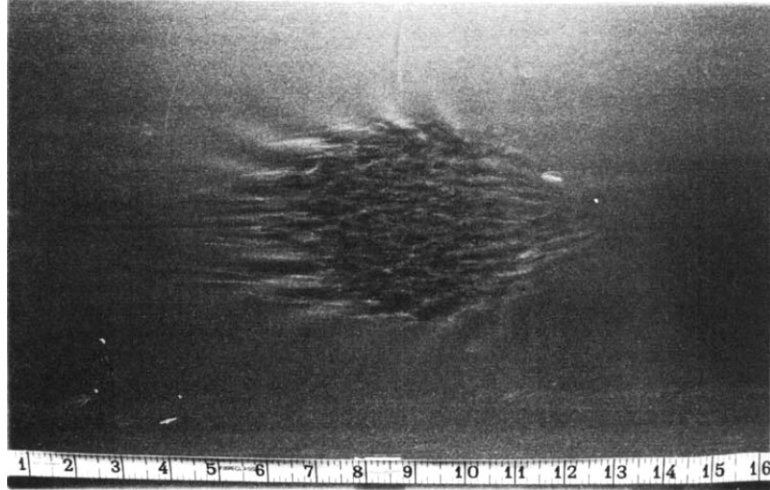
Figure 2.1 Turbulent spot as observed by Carlson *et al.* (1982). Flow direction from left to right, *Re* = 1000 and the scale indicates the distance from the disturbance in inches.

In a subsequent study, Alavyoon *et al.* (1986) expanded upon the work of Carlson *et al.* (1982) by investigating the spreading rate and propagation velocities of turbulent spots over a wider range of *Re*. Two channels with aspect ratios of 277 and 166 were used, and the *Re* range was from 1,100 to 2,200 based on half-channel height. The flow visualization technique employed was similar to that used by Carlson *et al.* (1982). Interestingly, it was observed that, unlike turbulent spots in the boundary layer, turbulent spots in channel flow lose their arrowhead shape and become concave as they travel downstream. Additionally, the researchers concluded that the ratio between the front and rear propagation velocities of the spot increases with *Re*.

In a more recent study, Sano & Tamai (2016) conducted an experimental investigation of transitional channel flow. The channel used in the study had an aspect ratio of 180, and metal-coated mica platelets were employed for flow visualization.

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The researchers injected artificial perturbations into the flow at the inlet, which either decayed or spread downstream depending on the *Re*. Snapshots of the flow visualization are presented in Figure 2.2.
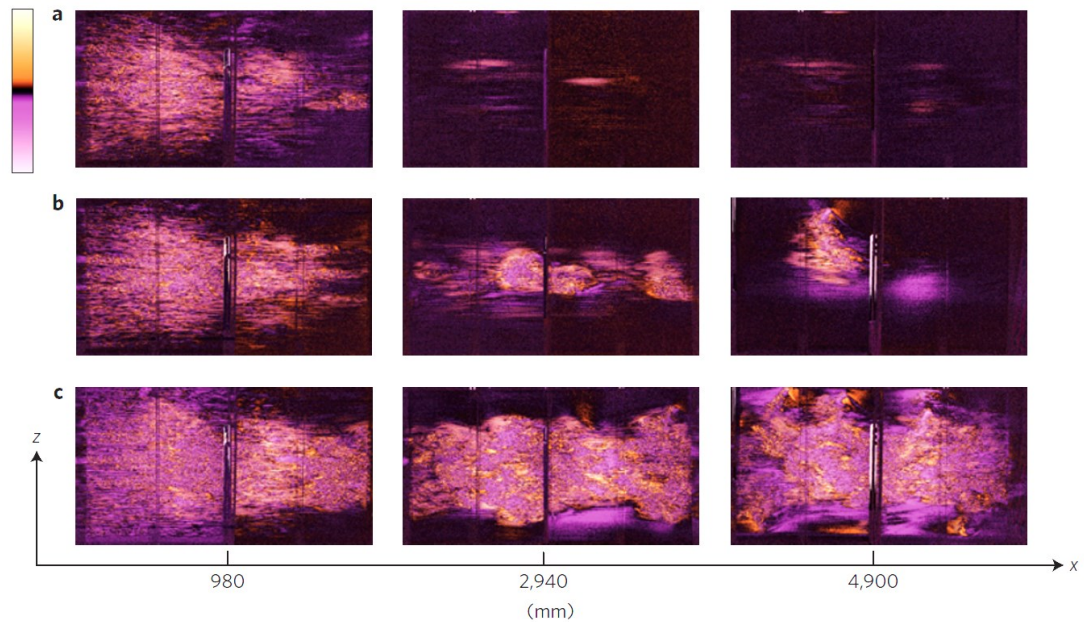
Figure 2.2 Turbulence spatial variation as observed by Sano & Tamai (2016). Dark regions represent laminar and bright regions show turbulent flow. Mean flow from left to right and the horizontal axis shows the distance from the perturbation. (*a*) *Re* = 798, (*b*) *Re* = 842 and (*c*) *Re* = 1005

Figure 2.2(*a*) shows that for *Re* = 798 (calculated based on channel half-height and centerline velocity), the injected perturbation separated into localized turbulent spots that quickly decayed as they propagated downstream. However, for *Re* greater than approximately 830, the researchers observed the splitting and spreading of turbulent

spots, as depicted in Figure 2.2(b). For sufficiently large Reynolds numbers, such as $Re \gtrsim 900$, the turbulent flow was sustained, as shown in Figure 2.2(c).

2.1.2 Critical Reynolds Number

Because of the gradual nature of the transition process, defining an explicit critical Reynolds number is intricate. As discussed in the previous section, localized patches of turbulent flow emerge in transitional wall-bounded flows, and they will either decay or grow depending on the Re. It is widely accepted to define the critical Reynolds number as a Re at which turbulence becomes sustained. Below we will introduce some studies that attempted to find the critical Reynolds number.

In a stability analysis of plane Poiseuille flow, Orszag (1971) analyzed the linear stability of PPf. He calculated the critical Re by solving the Orr-Sommerfield equation numerically using expansions in Chebyshev polynomials. The stability analysis calculated a critical Reynolds number of $Re = 5{,}772.22$. Below this Re, the laminar base flow can withstand infinitesimally small perturbations and retain the laminar state. However, early experiments showed that the flow becomes turbulent at much lower values of Reynolds number, even at $Re = 1{,}000$ (Narayanan & Narayana 1967; Patel & Head 1969).

To detect critical Re, Patel & Head (1969) carried out skin friction measurements in both pipe and channel flows. They calculated skin friction using the mean flow velocity profile. About the channel flow, it was found to be laminar until $Re \approx 1{,}350$. Afterwards, the transitional state appeared and was found to be in place until $Re \approx$

2,500-3,000. The fully turbulent state was thought to start with Reynolds numbers greater than $Re \approx$ 2,500-3,000. For the pipe flow, the transition regime is initiated at $Re \approx$ 2,000 and is terminated at $Re \approx$ 3,000.

Narayanan & Narayana (1967) along with their experimental investigation of channel flows, obtained the lower range of critical Re (for large disturbance) theoretically. They stated that the turbulent production and dissipation should be almost equal at the critical Re. Assuming a logarithmic law for the turbulent velocity profile, they calculated the critical Re to be 850. At that time, the lower critical Re obtained from experiments for pipe flow and channel flow was 2,000 (Lindgren 1957) and 1,025, respectively.

Seki & Matsubara (2012) carried out hot-wire anemometry in channel flow at transitional Re values. They defined lower marginal Re, the minimum Re for partial existence of sustainable turbulence, and estimated that to be around 1,400 based on the channel width and the bulk velocity. The upper marginal Re at which the intermittency factor reaches one is about 2,600. In the study of turbulence, the intermittency factor is defined as the fraction of time the flow remains turbulent at a specific given point of the flow field. The value of the intermittency factor can vary from 0 to 1. In this scaling, a zero value is assigned to a fully laminar region, and the value of one represents a fully turbulent flow. The initial idea of intermittency was proposed by Corrsin (1943).

Reference	Flow Geometry	Aspect Ratio	Transition Mechanism	Critical Re
Narayanan & Narayana (1967)	Channel	12	Disturbed	1025
Patel & Head (1969)	Channel	48	Natural	1300
Patel & Head (1969)	Pipe	-	Natural	2000
Orszag (1971)	Channel	∞	Natural	5772
Carlson et al. (1982)	Channel	133	Disturbed	1334
Alavyoon et al. (1986)	Channel	166, 277	Disturbed	1200
Avila et al. (2011)	Pipe	-	Disturbed	2040
Seki & Matsubara (2012)	Channel	52	Disturbed	1400
Barkley et al. (2015)	Channel	1	Disturbed	1700
Barkley et al. (2015)	Pipe	-	Disturbed	2000
Sano & Tamai (2016)	Channel	180	Disturbed	904

Table 1 Summary of some notable studies investigating critical Re in pipe and channel flows.

2.2 Laminar-Turbulent Transition in Non-Newtonian Flows

The transition mechanism to the turbulent regime in non-Newtonian fluids has significant importance due to the various applications of polymeric fluids. Polymer additives have long been considered highly effective drag-reducers. Toms (1948) observed that dissolving a small mass of polymers in a Newtonian solvent may considerably decrease friction drag in a high Re pipe flow compared to the pure solvent. A large and growing body of literature has investigated the "turbulent drag reduction" phenomenon (Toms 1977; Virk 1975; Virk et $al.$ 1997; White & Mungal 2008; Xi 2019). Nevertheless, much uncertainty still exists about the laminar-turbulent transition mechanism in polymeric flows and the transitional state of non-Newtonian flow.

The inaugurating research of Virk (1975) has demonstrated that the laminar-turbulent transition of a dilute polymer solution pipe flow occurs approximately at the same Re compared to Newtonian solvent. However, both delayed (Castro & Squire 1968; Draad et $al.$ 1998; Escudier et $al.$ 1998; Giles & Pettit 1967; White & McEligot 1970) and early transition (Forame et $al.$ 1972; Hansen & Little 1974; Zakin et $al.$ 1977) have been recorded in internal polymeric flow studies. While the transition happens at $Re \approx 2000$ for pipe flow and $Re \approx 1000$ for channel flow, it has been reported that transitional Re can approach values as low as 500 (Hansen & Little 1974;

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Hoyt 1977; Ram & Tamir 1964; Zakin *et al.* 1977). The following paragraphs will briefly survey the studies in transitional non-Newtonian shear-thinning fluid flows.

In the 1970s, different researchers noticed an increase in drag force for polymer solutions flow at low *Re* compared to the laminar value. In these low *Re* regimes, Newtonian fluids cannot sustain turbulence. The term "early turbulence" was commonly used to describe this phenomenon (Forame *et al.* 1972; Zakin *et al.* 1977). This phenomenon is thought to occur when a higher shear rate is obtained because of adequately small pipe diameter (or channel height) and high solvent viscosity. Ram & Tamir (1964) have illustrated that the onset of early turbulence is determined by shear stress rather than *Re*. It was also revealed that as molecular weight or concentration increases, the critical *Re* for the onset of early turbulence decreases. Nevertheless, the capillary diameter is inversely related to critical *Re*. The critical velocity at the onset of turbulence increases linearly with capillary radius. The early transition occurs regardless of inlet disturbances according to (1974). Zakin *et al.* (1977) pressure measurements revealed a smooth transition process to turbulence with reduced drag. No considerable pressure fluctuations were captured in contrast to what happens in Newtonian flows owing to intermittent puffs or slugs. Furthermore, they showed a deviation from the laminar pressure drop profile at *Re* = 1400, which is smaller than expected transitional *Re* in pipe flows. The onset of early turbulence can be recognized in the absence of pressure rise by the rise in turbulent intensity and the flattening of velocity profile, as these are two critical indicators of turbulence.

While the contradictory results of delayed or early transition could be attributed to the insufficient characterization of the polymer solutions used, theoretical studies have the same contrary conclusions too. On the one hand, calculations with rod-like suspensions predicted a delay in transition (Bark & Tinoco 1978). On the other hand, using the Maxwell model, it was noticed that elasticity in polymer solutions could lower the critical Re below which no linear growth of disturbances occurs (Porteous & Denn 1972a). These behaviours are respectively linked to the polymer configurations of coiled and stretched polymers. Virk (1975) assorted two distinct types of drag reduction behaviour; Type A for a coiled configuration and type B for a stretched configuration where a delay was observed in transition. Draad *et al.* (1998) carried out detailed experimental research of a pipe flow setup with natural transition Re = 60000 for water. In their setup, fresh polymer solutions with stretched conformation had a natural transition Re of 8000, and degraded, coiled configuration polymer showed transition at $Re \approx 30000$. The reduction in natural transition Re for polymeric solutions was not apparent. Their observation was attributed to a non-optimal design of the settling chamber contraction or a probable instability of the boundary layer in the entry region due to elastic effects (Porteous & Denn 1972a, 1972b). The friction factor of stretched configuration polymers departed smoothly from the laminar profile, with no distinctive spike visible during the Newtonian transition. The same polymer solution showed a spike in friction factor after being subject to mechanical degradation. Polymers demonstrated a stabilizing effect

concerning artificially triggered transition, and the transition was postponed to a higher *Re* than water (Draad *et al.* 1998).

Contrary to Newtonian flows, the *Re* is not the only non-dimensional parameter for characterizing the transition of non-Newtonian flows. Weissenberg number is another dimensionless number to consider which compares the elastic forces to the viscous forces, and it can be calculated as follows $Wi = \lambda \dot{\gamma}$ (in which λ is relaxation time and $\dot{\gamma}$ is the flow shear rate). As one can point out, *Wi* is dependent on the velocity profile of the flow through shear rate. In contrast to *Wi*, elasticity number $E = \lambda v / R^2$ is only dependent on the polymer solution's physical properties and the length scale of internal flow. Therefore, it can be seen that *Wi* and *E* are both highly dependent on the flow length scale (pipe diameter or channel height).

The early turbulence phenomenon was found mainly in tubes with smaller diameters, but there was little consensus on it in prior studies. Moreover, as mentioned before, the polymer solutions were not precisely characterized in most earlier experiments. Nonetheless, Samanta *et al.* (2013) showed that polymer solutions might undergo early turbulence, and Srinivas & Kumaran (2017) also suggested that rectangle channel flow may go through a similar early transition process. The considerably high polymer concentrations of their solution and the substantially smaller diameter of the tube used by Samanta *et al.* (2013) helped them achieve significantly greater elasticity numbers. Moreover, it allowed them to probe previously unexplored parametric regimes, which is a major difference between their studies and those of others. Indeed, higher elasticity numbers may be responsible for

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observing early transition in their study. For example, Draad *et al.* (1998) noticed a drop in the natural transition *Re* (≈40000) with polymer addition but did not observe early turbulence. The recent experiments of Chandra *et al.* (2018, 2020) reported a decrease in the transitional threshold while increasing solution concentration in the range of 300 to 800 parts per million or ppm and substantiated the observations of Samanta *et al.* (2013).

Dubief's group has conducted simulations to examine the existence of elasto-inertial turbulence in high elasticity (*E*) solutions (2013; 2018; 2015). Their results extensively illustrate the possibility of "early turbulence" in polymeric solutions with sufficiently high *E*. These observations were in agreement with Samanta *et al.* (2013) experiments. The elasticity number is linked to the polymer solution's longest relaxation time. Due to lower polymer concentrations used for drag reduction studies (≈50 ppm), the elasticity number is significantly lower in those experiments than in recent studies that aim to observe "early turbulence.". This fact could be the cause for the absence of early turbulence in drag reduction experiments.

Pan *et al.* (2013) experimentally investigated the instabilities and transition in a long straight microchannel. They disturbed the flow with a number of obstacles at the entrance. Particle image velocimetry was used to capture the velocity profile in addition to dye convection experiments. The result suggested that polymeric fluids in a parallel shear flow can go through a nonlinear subcritical instability at low *Re*. However, the *Re* scale was too small (*Re* < 0.01) in their experiments because of high solution viscosity and small channel height. They also stated that the critical

Weissenberg number value for the onset of the subcritical instability in the parallel flow is $Wi = 5.2$ for the disturbance type and level they had in the experiments.

Poole (2016) conducted experiments to study shear-thinning polymer solution flow through both pipe and rectangular channel. The mean velocity profiles at low flow rates appear steady and align with results determined analytically from steady-shear rheology data. At a flow rate higher than the critical flow rate, the mean velocity close to the wall becomes weakly time-dependent, and its magnitude increases with increased flow rate until it reaches saturation. The flow will have a nonmonotonic distribution of velocity gradients, a reduction in wall shear rate, and an overshoot of mean flow velocity close to the duct center because of these fluctuations. As a result of the reduced wall shear rate, the stability leads to a reduction in drag.

In Srinivas & Kumaran's (2017) study, one wall of the channel facility was made from soft material. Although it has been referenced in literature as an example of polymeric channel flow, it is not clear whether the softness of the wall can affect the transition phenomenon or not. The channel height they tested was 160 μm, and it had a laminar turbulence transition at $Re \approx 290$ for water. They found a concentration threshold below that, in spite of the attenuation of turbulence, the transition Re remains unchanged. When the polymer concentration increases beyond the threshold, there is a decrease in the transition Re and the intensity of the turbulent fluctuations. The highest concentration they used reduced the transition Reynolds number to $Re \approx$ 115.

The flow of viscoelastic fluid in parallel shear geometry at low Re values is investigated experimentally by Qin and Arratia (2017). They used 300 ppm polyacrylamide solution in a straight duct with 100 μm sides. It was demonstrated that even at low Re, polymeric fluids flowing in parallel shear geometries could sustain large velocity fluctuations in space and time.

Graham and colleagues (2017) conducted direct numerical simulations on a transitional viscoelastic channel flow. They found a relation between the intermittency of transition of viscoelastic flows and their previously proposed "active and hibernating turbulence" hypothesis (Xi & Graham 2010). When friction Reynolds numbers are increased at a fixed Weissenberg number, the hibernating zones disappear. So the flow is more in the "active" turbulence state; however, these hibernating regions reemerge once viscoelasticity increases and progressively dominate the flow fields at sufficiently high Wi.

The onset of transition in polymeric flows through microtubes was experimentally studied by Chandra et $al.$ (2018). They examined microtube diameters ranging from 390 μm to 470 μm and solution concentrations from 50 to 800 ppm. Due to the small diameter of tubes and high concentration of solutions, the elasticity number E of their experiments was relatively higher compared to previous studies. Their facility had a natural transition of $Re \approx 2000$ for the Newtonian case. It was illustrated that increasing polymer concentration first delays the onset of the transition, resulting in a higher transition Re of 2500. With further increases in polymer concentration, the Re

for transition decreases. The polymer is observed to destabilize the flow at sufficiently high concentrations, and the transition occurs as low as 800.

Choueiri *et al.* (2018) have proposed that the drag reduction resulting from utilizing polymers can go further than the maximum drag reduction (MDR) in a specific domain of parameters. A 10 mm diameter glass pipe was used to test polymer solutions with various concentrations. Newtonian natural transition Re of their facility was 2800. For concentrations under and equal to 20 ppm, they observed a delay in the onset of turbulence up to $\sim$25% larger Re. With increasing Re to higher values in the low concentration regime, turbulent puffs and slugs were observed. Higher concentrations ($C \gtrsim 90$ ppm) will lead to elastoinertial instabilities at Re well below those associated with Newtonian turbulence.

In a recent study, Chandra *et al.* (2020) conducted experiments to study early transition in micro-tubes with diameters of 0.49 to 2.84 mm. They observed a delay in the onset of turbulence for lower concentrations of the added polymer. Still, as the concentration is increased further, the transition Re drops below 2000, which is transition Re in Newtonian pipe flows. In small concentrations of polymers, if the Re is kept above the transition Re value for Newtonian flows, and the polymer concentration is gradually increased, the flow will relaminarize, and the friction factor will decrease. They also state that the flow undergoes a transition due to elasto-inertial instability as the polymer concentration increases further.

Krishnan *et al.* (2021) utilized velocimetry in a 100 mm diameter pipe to investigate the laminar-turbulent transition of a shear-thining fluid flow. During

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transitions, intermediate structures (puffs and slugs) were observed to form similar to Newtonian transition. The transition occurred in different Reynolds numbers due to their various slurry solutions; however, a delay in transition Re was recorded in general.

Reference	Flow Geometry	Polymer	Concentration (ppm)	Flow Length Scale (mm)	Transition Mechanism	Critical *Re*
Draad *et al.* (1998)	Pipe	PAMH	20	40	Natural	8000
Samanta *et al.* (2013)	Pipe	PAM	500	4	Natural	800
Srinivas & Kumaran (2017)	Channel	PAM	50	0.160	Natural	300
Chandra *et al.* (2018)	Tube	PAM	800	0.390	Natural	800
Chandra *et al.* (2018)	Tube	PAM	600	0.49	Natural	1080
Chandra *et al.* (2018)	Tube	PAM	600	2.84	Natural	1462
Chandra *et al.* (2018)	Tube	PAM	800	0.49	Natural	970

Table 2 Summarizing experimental studies on laminar to turbulent transition of polyacrylamide solutions

2.3 Elasto-Inertial Turbulence

In the '70s, Forame *et al.* (1972) and Zakin *et al.* (1977) made the first observations that polymers cause instability in dilute polymer solutions. These pipe studies observed a friction factor deviation from Poiseuille's law at a Reynolds number below transitional *Re* of water.

Samanta *et al.* (2013) had a breakthrough insight into these observations by exploring the flow of polymer solutions in pipes at various concentrations. They observed that for sufficiently high concentrations (500 ppm), the flow goes through a direct transition from a laminar to a chaotic state. This transition even happened at *Re* = 800, which is well below the expected transitional *Re* for Newtonian pipe flow. This qualitatively distinct chaotic flow regime was named "Elastoinertial turbulence" or EIT. Chandra *et al.* (2018) observations were consistent with Samanta *et al.* (2013) as they first noticed a delay in transition. Increasing concentration led to the transition to EIT at *Re* = 800.

There have been more experimental studies of viscoelastic transition in pipes, but Srinivas and Kumaran (2017) showed that the transition state is qualitatively similar in soft-walled microchannels. In their experiments, transition *Re* dropped from 300 to 35 for sufficiently high concentrations.

Based on the results described thus far, dilute polymer solutions with sufficient viscoelasticity show robust behaviour in the early transition. The new flow regime following this early transition, referred to as elasto-inertial turbulence (EIT), appears

to display distinct characteristics compared to Newtonian turbulence. The findings point to polymer-driven self-sustaining mechanisms that can support this chaotic flow state with friction factor scalings remarkably close to MDRs (Samanta *et al.* 2013). Nevertheless, EIT remains an active research area as a complete understanding of its mechanisms is still lacking.

Pipe flow experiments by Choueiri *et al.* (2018) provided critical insights into EIT mechanisms. Researchers observed the relaminarization of Newtonian turbulence at low transitional $Re = 3150$ when polymer concentration was increased in a quasi-static manner. This relaminarization was followed by a "reentrant transition" to EIT marked by "weak, elongated streaks" of flow. The friction factor increased to the MDR limit with this reentrant transition for the chosen parameter set. As a result of these experiments, one can identify two distinct mechanisms of chaos in dilute polymer solutions: Newtonian turbulence, inhibited by viscoelastic flow and elastoinertial turbulence promoted by viscoelasticity. The authors observed a monotonic drop in friction factor at higher transitional Re (5200 and 10000), which appears to be the more traditional way to convert Newtonian turbulence to MDR. At these higher Re regimes, the flow state at MDR remained similar to EIT with weak, elongated velocity streaks.

Graham summarized observations and experiments of polymer solutions to illustrate the "parameter space" qualitatively, as shown in Figure 2.3. The elasticity number remains constant on oblique lines shown in the figure. Path A shows studies which keep Re constant and increase Wi to explore the parameter space. These studies

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demonstrate a direct pathway from Newtonian turbulence, which leads to EIT. Observations made by Choueiri *et al.* (2018) are shown as path B. They kept *Re* at 3150 and increased solution concentration, resulting in higher viscoelasticity. Increasing viscoelasticity, they first noticed a relaminarization followed by the transition to EIT. Some polymer drag reduction studies (Escudier *et al.* 2009; Ptasinski *et al.* 2001) report a decrease in velocity fluctuations and Reynolds shear stresses as viscoelasticity increases, which points towards the weakening of near-wall Newtonian turbulent structures. Likewise, as the flow rate increases, we see the switch from Newtonian-style turbulence to MDR/EIT in Path C. According to experimental results by (Forame *et al.* 1972; Samanta *et al.* 2013; Zakin *et al.* 1977), at a sufficiently high elasticity number, a laminar flow can directly go through a transition to a two-dimensional flow with a significantly lower friction factor or better known as EIT, as demonstrated by path D.

Although extensive research has been carried out on polymeric flows, no single experimental study exists that addresses flow states and structures in transition to turbulence. This indicates a need to understand the various perceptions of flow structures that exist among transition. This thesis will investigate the laminar-turbulent transition in non-Newtonian flows.
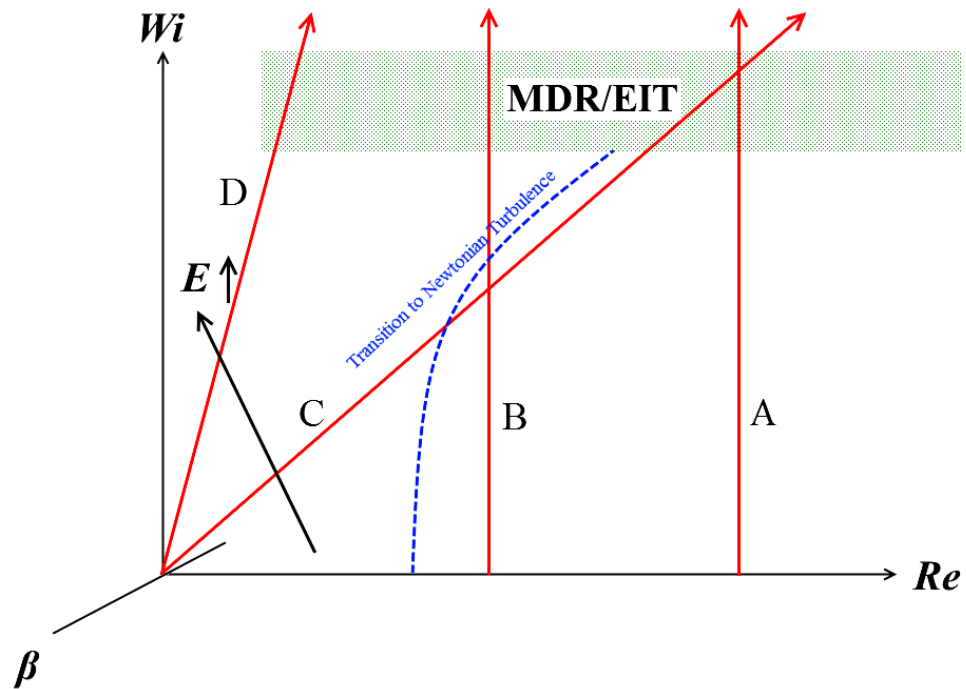
Figure 2.3 The parameter space of turbulence in dilute polymer solutions. Regenerated figure inspired by (Graham 2014; Shekar 2021; Xi 2019). Boundaries shown here are not necessarily vertical or horizontal, and they might be fuzzy.

3. Experimental Methodology

This thesis encompasses three distinct experimental campaigns, each designed to achieve specific objectives. The first experiment employs two-dimensional time-resolved Particle Image Velocimetry (PIV) in the streamwise-wall-normal plane to investigate the transitional behaviour of water and polymeric flows across a wide range of Re. The second experiment focuses on collecting long-duration data sequences using double-frame data acquisition to explore the statistical properties of transitional flows. In the third experiment, the streamwise-spanwise plane is examined to study turbulent spots. The outcomes of these experiments for water flow are compared with prior experimental findings and numerical studies to assess the accuracy of the measurements.

The methodology employed in these experiments is detailed in five sections. The first section provides an overview of the flow loop utilized in the experiments. The second and third sections delve into the preparation of the polymer solution and the rheological measurements, respectively. The fourth section outlines the streamwise-

wall-normal plane PIV setup and the image processing procedure employed. Lastly, the fifth section describes the streamwise-spanwise plane PIV setup and the corresponding image processing procedure.

3.1 Flow Facility

This section delineates the gravity-driven closed-flow loop apparatus employed for conducting the experiments. A schematic representation of the flow facility can be found in Figure 3.1. The apparatus comprises an elevated reservoir, a settling chamber, a test section, a diffuser, and a downstream tank. As shown in Figure 3.1 the x, y, and z axes are in the streamwise, wall-normal and spanwise directions, respectively, and the coordinate system is placed on the channel centerline.

The upstream reservoir, situated 2.6 meters above the test section centerline, has a capacity of 190 litres. The pressure head generated by this elevated reservoir propels the flow within the loop. A 254 mm pipe connects the upstream reservoir to the settling chamber. The settling chamber spans approximately 2 meters in length and features two designated slots for installing honeycombs and meshes. Two layers of honeycombs coupled with mesh layers are installed at distances of 155 mm and 1655 mm from the settling chamber entrance, as well as 3685 mm and 2185 mm upstream of the measurement location. The maximum cross-section of the settling chamber measures 596×254 mm.

Connected to the end of the settling chamber is a nozzle with a length of 0.75 meters and a contraction ratio of 48:1, designed to minimize turbulence and non-

uniformity in the test section. The test section, fabricated from acrylic, has dimensions of full height (H) 16 mm, half height (h) 8 mm, width (W) 200 mm, and length (L) 2390 mm. This results in an aspect ratio of $W/H = 12.5$ and a length-to-height ratio of $L/H = 149$. The inlet section and connections between all channel components are meticulously designed and constructed to be as smooth as possible, thereby reducing upstream perturbations. The flow rates achieved during the experiments ranged from a minimum of 0.1 l.s-1 to a maximum of 2.5 l.s-1.
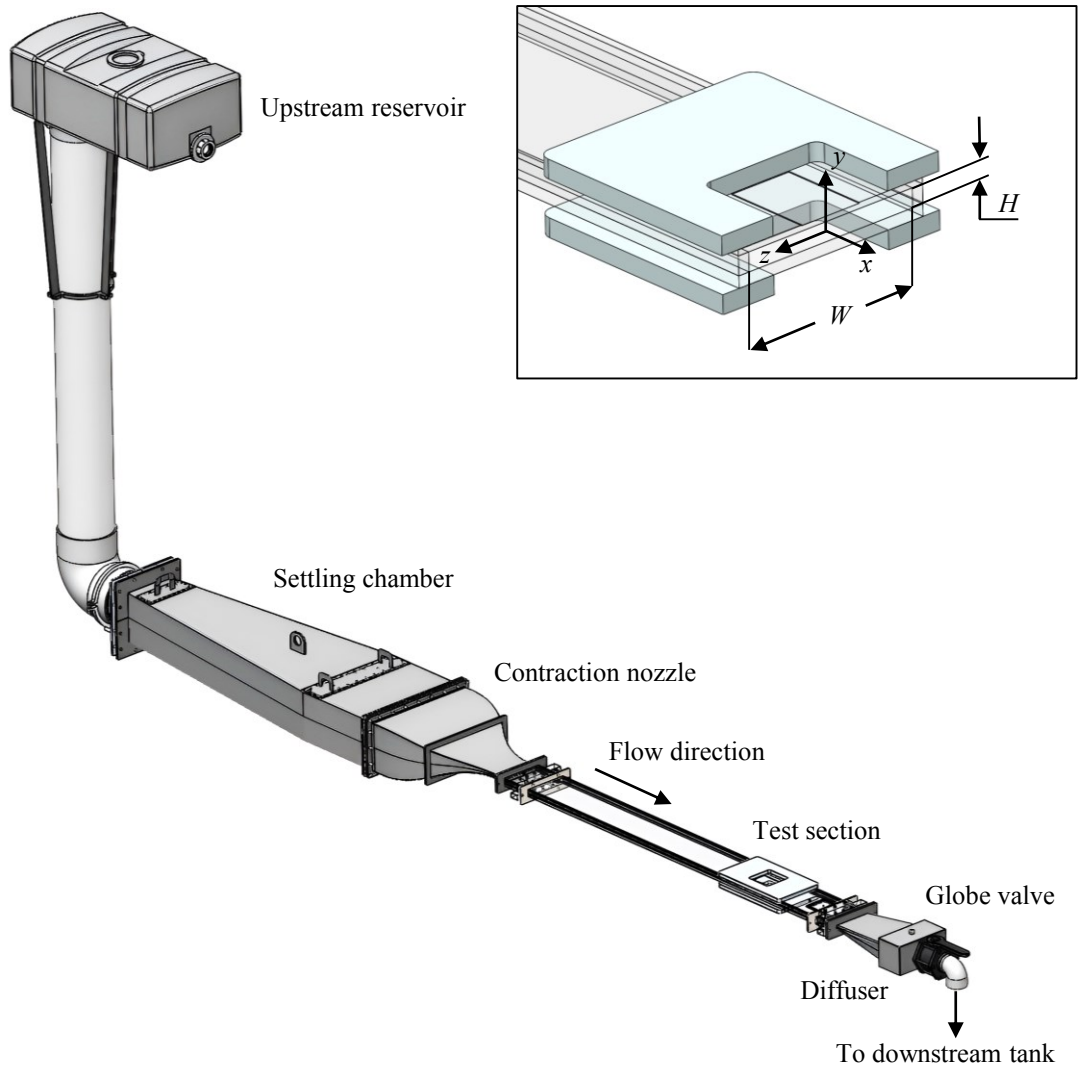
Figure 3.1 Annotated schematic view of the experimental facility. The inset shows the cross-section of the test section and the coordinate system.

After passing through the test section, the flow enters a diffuser and is subsequently directed into a downstream tank with a capacity of 760 litres. To maintain consistency, the upstream reservoir is filled to the same level before each experiment. The upstream reservoir can be refilled using a progressing cavity pump (Moyno 36704)

connected to a 1.5 kW motor from the downstream tank to the upstream reservoir placed at the ceiling. The pump's maximum rotational speed is 1755 rpm, regulated by a variable frequency drive (VFD). The acquired signal from the PMC VersaLine® VL3000 level transmitter was fed to National Instruments LabVIEW software, and an output signal was sent to VFD to control the pump and ensure the upstream reservoir was filled to the same level before each experiment. To initiate every experiment, the desired fluid stored in the downstream tank was used to fill the facility.

The loop operating procedure can be described in detail through the following steps:

1. Initiation of the experiment: To begin each experiment, the fluid of choice, which is stored in the downstream tank, is used to fill the facility. This ensures that the desired fluid is readily available for the experiment.

2. Flow rate control: In order to regulate the flow rate of the fluid, a high-precision globe valve is employed. This valve can be adjusted to specific openings, allowing for precise control over the flow rates required for each experiment.

3. Measurement completion: Once the necessary measurements have been taken, the fluid flow is stopped by closing the high-precision globe valve. This ensures that the fluid flow is halted at the appropriate time, allowing for accurate data collection.

4. Refilling the ceiling reservoir: After the fluid flow has been stopped, a feedback control system is utilized to refill the ceiling reservoir to a constant

level. This is done to maintain consistent experimental conditions for each trial, ensuring that the results are reliable and reproducible.

For each solution, at least eight valve openings were tested ranging from laminar flow conditions to turbulent, with each opening being repeated at least five times to ensure accuracy and consistency. Furthermore, to investigate the transitional state, an additional six repetitions of measurements were conducted for the valve openings in the transitional flow rate. The valve openings tested for each solution are shown in Table 3. These rigorous testing procedures were employed to ensure the repeatability and statistical convergence of the experimental results. The change in fluid pressure head was less than 10% when compared to the initial state before the experiment and after its termination, even at the maximum flow rate of 2.5 l/s. Furthermore, examining the flow rate during the data acquisition process revealed that any variations were negligible. Then a feedback control system was used to fill up the ceiling reservoir to a constant level each time with the pump rotation speed being limited to 440 rpm.

Water	50 ppm	75 ppm	100 ppm	150 ppm
1/8	1/4	1/2	3/4	3/4
1/4	1/2	3/4	1	1
1/2	3/4	1	1 1/4	1 1/4
3/4	1	1 1/4	1 1/2	1 1/2
1	1 1/4	1 1/2	2	2
1 1/4	1 1/2	2	2 1/2	2 1/2
1 1/2	2	3	3	3
×	×	5	4	4
×	×	8 1/2	5	5
×	×	×	6	6
×	×	×	7	7
×	×	×	×	10

Table 3 Valve Openings Tested for Each Solution. The valve openings are presented in units of turns of the valve opening. A 1" globe valve was used for the 50 ppm and 75 ppm solutions. A 1 1/2" globe valve was used for the 100 ppm and 150 ppm solutions.

3.2 Polymer solution preparation

The chosen drag-reducing additive for these experiments is a flexible polymer, polyacrylamide (PAM) (SNF Floerger, 6030S), which has a molecular weight of 30-35 MDa. The chemical structure of PAM is shown in Figure 3.2. Four concentrations of PAM were considered for the study: 50, 75, 100, and 150 parts per million (ppm).

$$
\left[CH_2 - HC \begin{array}{c} \\ | \\ C = O \\ | \\ NH_2 \end{array} \right]_n
$$
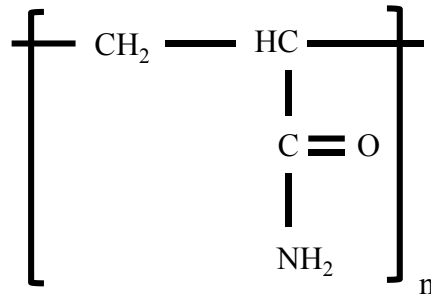
Figure 3.2 shows the molecular structure of polyacrylamide (PAM), the drag-reducing polymer used in the experiments.

The preparation process begins with accurately weighing the solid polymer powder using an Ohaus E11140 Explorer digital scale, which offers a resolution of 0.1 mg. The weighed powder is then gradually added to 170 litres of tap water in a cylindrical tank, ensuring a slow and controlled dispersion to prevent the formation of clumps or aggregates. This mixture forms a concentrated master solution.

To facilitate thorough mixing and dispersion of the polymer, a mixer (LIGHTNIN LabMaster L5U10F) equipped with a three-blade marine impeller with a 75 mm diameter is employed. The mixer agitates the master solution at a speed of 75 rpm for

two hours, promoting the formation of a homogeneous solution and minimizing the risk of mechanical degradation.

Once the initial mixing is complete, the master solution is drained into the downstream tank and diluted to the desired concentration using additional tap water. The pump is then used to circulate and gently mix the 720-litre PAM solution within the downstream tank for another two hours at a rotational speed of 225 rpm. This secondary mixing step ensures that the diluted polymer solution is uniform and free of any concentration gradients.

After completing the mixing process, the resulting solution is left to rest for 15 hours overnight. This resting period allows any residual air bubbles, impurities, or undissolved polymer particles to dissipate or settle, further enhancing the homogeneity and quality of the prepared polymer solution.

On the following day, the pump, operating at a rotational speed of 225 rpm, is utilized to fill the upstream reservoir with the PAM solution. This step ensures that the experimental setup is primed and ready for conducting the tests with the carefully prepared polymer solution. The meticulous preparation process described in this section is crucial for obtaining reliable and consistent results in the subsequent experiments involving drag reduction and flow dynamics.

3.3 Rheology measurements

3.3.1 Shear viscosity measurements

Viscosity is a critical parameter in investigating polymer drag reduction, and its impact on the rheological properties of the fluid cannot be overstated. It is well-known that the addition of a specific amount of polymer to a Newtonian fluid can transform it into a non-Newtonian fluid. Thus, in this study, we will be examining the shear viscosity or apparent viscosity. The rheological characterization of polymer solutions will be conducted using a torsional rheometer (HR-2, TA Instruments) equipped with a cone and plate geometry.

To accurately characterize rheology, it is necessary to measure viscosity at various shear rates for non-Newtonian fluids. A depiction of the cone and plate geometry of the rheometer is presented in Figure 3.3. The rheometer comprises a cone affixed to a rotor and a stationary plate. While the plate remains stationary, the cone is driven by a motor. The geometry used had a radius of $R = 30$ mm and an angle of $\beta = 2^{\circ}$. Additionally, a temperature control system is attached to the rheometer to maintain the desired temperature.
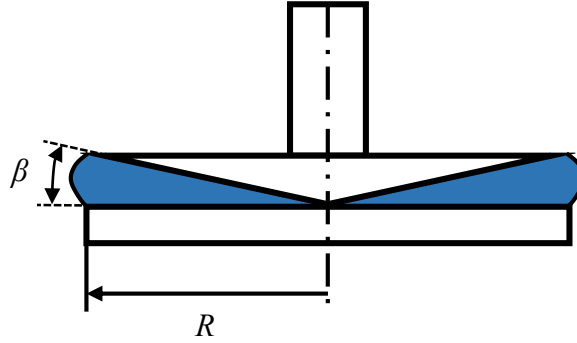
Figure 3.3 illustrates a schematic diagram of the cone and plate rheometer used to measure the shear viscosity of the test solutions.

Viscosity measurements were taken at a constant temperature of 25˚C and a shear rate of up to 200 s^{-1}. For Newtonian fluids, viscosity is shear rate independent. However, with the introduction of polymers to solutions and increasing their concentration, a considerable increase in solution viscosity occurs, leading to non-Newtonian behaviour. Specifically, polymer solutions exhibited shear-thinning behaviour, meaning that viscosity decreases as the shear rate increases. This behaviour is more pronounced at higher polymer concentrations, as expected.

Figure 3.4 shows the shear viscosity μ of solutions with increasing shear rates $\dot{\gamma}$. All PAM solutions demonstrate noticeable shear-thinning but to varying degrees. Here, shear-thinning is well described by the power-law model of (3.1), which was fit on measurements of μ as a function of $\dot{\gamma}$.

$$\mu = K \dot{\gamma}^{n-1},$$ (3.1)

the model parameters are presented in Table 4. Note that the rate-index n describes the slope in μ with increasing $\dot{\gamma}$ and the degree of shear-thinning – as n decreases the

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solution becomes more shear-thinning. Error bars show the standard deviation of five samples taken from the channel flow facility, each of which corresponds to a set of various valve openings tested with the same solution.
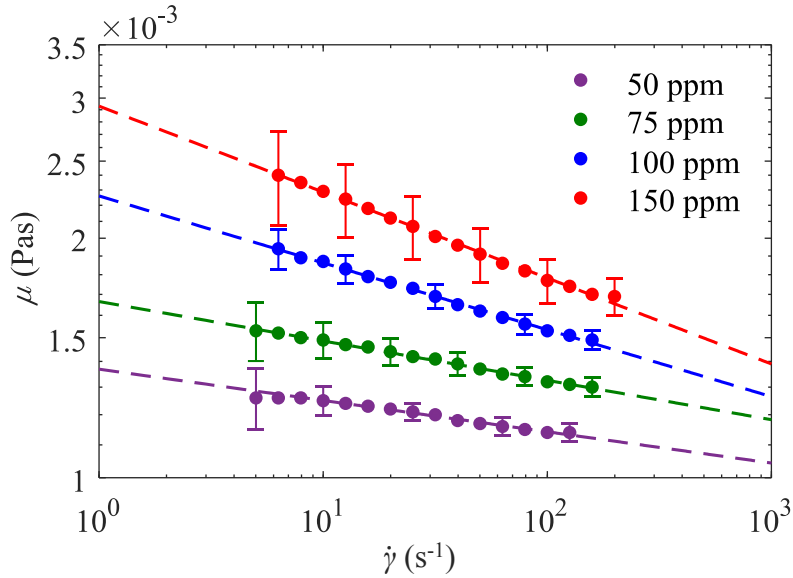

Figure 3.4 The relationship between shear rate and apparent viscosity is demonstrated for four polymer solutions, highlighting the fluids' rheological behaviour.

3.3.2 Extensional rheology measurements

A bespoke dripping-onto-substrate (DoS) apparatus was utilized to evaluate the extensional rheological properties of PAM solutions. In the employed method for measuring, a minuscule droplet was released from a flat-tipped nozzle featuring a diameter (D_0) of 1.27 mm. A syringe pump (Legacy 200, KD Scientific Inc.) facilitated the expulsion of the droplet at a rate of 0.02 ml min^{-1}. The pumping process

ceased when the droplet came into contact with a glass substrate positioned 3D0 or 3.81 mm beneath the flat-tipped nozzle outlet. Upon contact with the substrate, a liquid bridge formed between the nozzle outlet and the substrate. The liquid bridge's diameter (D_{min}) experienced a rapid reduction due to capillary forces. A schematic of the DoS setup is illustrated in Figure 3.5.
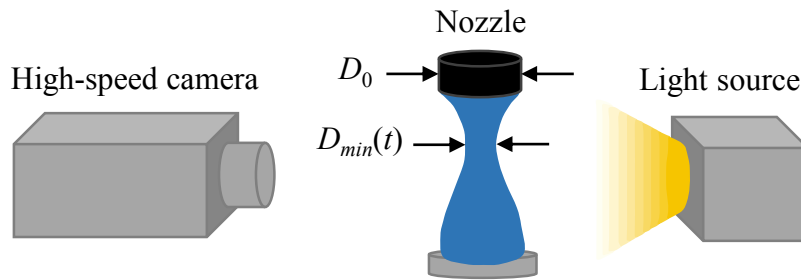
Figure 3.5 shows a schematic representation of the dripping-onto-substrate (DoS) experimental setup which was employed to evaluate the extensional rheological properties of the polymer solutions..

A high-speed camera (v611, Vision Research) and LED backlighting were utilized to capture images of the liquid bridge. The camera was equipped with a 1280 × 800 pixel complementary metal-oxide semiconductor sensor, with pixel dimensions of 20 × 20 μm^2 and a 12-bit depth. A zoom lens provided a magnification of 3.8 and a scale of 5.16 μm pixel^{-1}. Images were acquired at a rate of 2 kHz. The liquid bridge's minimum diameter (D_{min}) was ascertained using a MATLAB (MathWorks Inc.) script.

The Ohnesorge number, $Oh = t_v/t_R$, establishes a connection between the time scale linked to viscous forces and the Rayleigh time t_R, which is associated with surface tension and inertial forces. In this case, $t_v = \eta D_0/2\sigma$ represents the characteristic time

scale for visco-capillary thinning, $t_R = (\rho D_0^3/8\sigma)^{1/2}$, and σ denotes the surface tension. When $Oh > 1$, viscous forces play a significant role, and the evolution of D_{min} is characterized by visco-capillary thinning, $D_{min}(t)/D_0 = 0.0709(t_b-t)/t_v$. For elastic fluids, the Deborah number, $De = t_e/t_R$, indicates the proportion between the extensional relaxation time t_e and the Rayleigh time. If $De > 1$, the necking process is primarily influenced by elastic and capillary forces. This elastocapillary (EC) regime is represented by:

$$\frac{D_{min}(t)}{D_0} = A \exp(-\frac{t}{t_e}), \tag{3.2}$$

where A is a constant. Figure 3.6 illustrates the impact of polymer concentration on filament diameter over time, with zero time signifying the moment the droplet is released. Error bars are determined by calculating the standard deviation of five repeated measurements, each performed on samples obtained prior to flow measurements in the channel flow facility. A noticeable increase in resistance to capillary force is observed at 75 ppm compared to 50 ppm. It is evident that dilute polymer solutions experience a faster filament breakup than concentrated polymer solutions, which can be attributed to the lower elasticity in dilute polymer solutions. Polymer solutions with higher relaxation times exhibit greater elasticity (Marshall & Metzner 1967). Delshad *et al.* (2008) also employed relaxation time to represent elasticity in polymers within a viscoelastic model. Furthermore, it is apparent that the solution's resistance to capillary force escalates with increasing polymer

concentration. Consequently, concentrated polymer solutions possess a higher stretching potential compared to dilute polymer solutions.
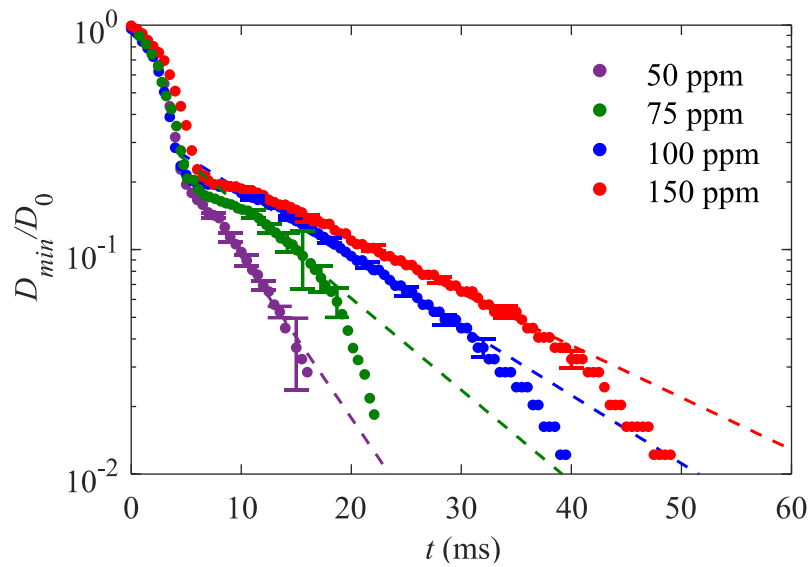
Figure 3.6 Semi-logarithmic plot of filament diameter as a function of time for four distinct polymer concentrations.

Concentration (ppm)	K (Pa s^n)	n	t_e (ms)
50	1.37×10^{-3}	0.961	2.0
75	1.67×10^{-3}	0.951	3.5
100	2.26×10^{-3}	0.916	4.7
150	2.93×10^{-3}	0.892	6.1

Table 4 Parameters used in equation 1 for each PAM solution are shown. Additionally, the relaxation times calculated from DoS measurements are also displayed.

3.4 Particle image velocimetry (PIV)

Three separate test campaigns have been conducted in this study: double-frame data collection with extended acquisition times in the streamwise-wall-normal plane, time-resolved data collection in the streamwise-wall-normal plane, and double-frame data collection with extended acquisition times in the streamwise-spanwise plane. The double-frame data collection with extended acquisition times, hereafter referred to as long-duration, involves collecting a large number of image pairs at a lower sampling rate to capture the evolution of flow structures over long time periods. In contrast, the time-resolved data collection refers to acquiring single-frame images at higher sampling rates to provide better temporal resolution of the flow field. However, the maximum duration of time-resolved measurements is limited by the memory of the high-speed camera. Particle image velocimetry (PIV) was used to measure the velocity of the fluid within the test section. The PIV system consisted of a high-speed camera (v611, Phantom) and a dual-cavity Nd:YLF high-repetition laser (DM20-527 Photonics Industries). The high-speed camera has a 1280×800 pixel complementary metal oxide semiconductor (CMOS) sensor with a pixel size of 20×20 μm^2 and a resolution of 12 bits. The laser beam has a wavelength of 532 nm, and maximum pulse energy of 20 mJ $pulse^{-1}$. A programmable timing unit (PTU X, LaVision GmbH) synchronized the camera and laser. The flow was seeded with 2 μm diameter silver-coated solid glass spheres (Potters Industries Conduct-O-Fil® SG02S40). PIV measurements were taken along two fields of view (FOV). The first being along the

streamwise-wall-normal plane, and another along the streamwise-spanwise plane. The PIV configuration is described for each test campaign in this section.

3.4.1 Long-duration wall-normal PIV

In this test campaign the goal was to collect long data sequences of streamwise wall-normal velocity fields of the transitional Reynolds number range for each solution. A plano-convex spherical lens with a focal length of $f = +200$ mm and a cylindrical lens with a focal length of $f = -20$ mm were used were utilized to form a laser sheet with a thickness of 1 mm and a width of 160 mm in the x direction for streamwise-wall-normal measurements. The camera was equipped with a Sigma lens that had an $f/11$ aperture and a focal length of $f = 105$ mm. The sensor resolution was decreased to 1280×312 to allow for longer data acquisition times and recording rates when necessary.

This test campaign involved the acquisition of double-frame images at a rate of 60 Hz. The temporal delay between the two laser pulses utilized for double-frame measurements was varied from 700 to 6900 μs and was set accordingly for each flow rate. The desired particle shift was 8 to 12 pixels. Each dataset comprised 13,569 double-frame images. This measurement scheme facilitated extended data collection periods of This measurement scheme permitted long data collection times ranging from approximately $500T$ to $2700T$ corresponding to the lowest and highest Re respectively, where $T = H/\langle U_c \rangle$ is a representative time scale of the flow.

The velocity vectors for each measurement were calculated using DaVis 8.4 software from LaVision GmbH. The first step involved subtracting the minimum

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image intensity from each dataset. Subsequently, the intensity of each image was normalized by the average intensity of the entire image ensemble. Velocity vectors were computed using cross-correlation with a final interrogation window size of 32×32 pixels (0.45×0.45 mm) and an overlap of 75% between adjacent interrogation windows.

3.4.2 Time-resolved wall-normal PIV

The objective of this experimental campaign was to enhance the temporal resolution of flow-field measurements. Additionally, the investigation encompassed the evaluation of both higher and lower Reynolds numbers to ensure the accuracy of the transitional Reynolds number range that was obtained.

Similar to long duration wall-normal setup, a combination of lenses was used to shape the laser beam into a laser sheet with 1 mm thickness and 160 mm width in the x direction. A Sigma lens with a focal length of $f = 105$ mm and an aperture of $f/11$ was connected to the camera. Sensor resolution was reduced to 1280×312 to achieve the maximum duration of data recording.

In order to acquire time-resolved data, single-frame images were obtained at acquisition rates ranging from 0.2 to 9 kHz. Like the double-frame measurements, the single-frame datasets also consisted of 13,569 images. However, due to the higher acquisition rates, the duration of the single-frame datasets was much shorter. As previously mentioned, eight valve openings were tested ranging from laminar flow conditions to turbulent utilizing the single frame, time-resolved measurement scheme.

The additional six repetitions of valve openings with transitional flow rates were investigated using long-duration double-frame acquisition.

The velocity vectors were calculated using DaVis 8.4 software from LaVision GmbH. The image pre-processing steps were similar to long-duration double frame acquisition. Then the velocity vectors were computed using a sliding ensemble correlation with a final interrogation window size of 32×32 pixels (0.55×0.55 mm) and an overlap of 75% between adjacent interrogation windows. Three correlation maps were averaged over a time period that, based on the acquisition rate, ranged from 6.5×10^{-4} to 0.01 seconds in the flow.

3.4.3 Long-duration spanwise PIV

In order to observe turbulent spots from the streamwise spanwise field of view, long-duration double frame data acquisition was conducted for transitional Reynolds numbers of all solutions.

The laser sheet was positioned in the xz plane at a distance of $y = 0$ from the wall in measurements taken in the streamwise-spanwise plane. The thickness of the laser sheet was around 1.5 mm and its width in the x direction was about 70 mm. A camera lens from Nikon with a focal length of $f = 60$ mm and an aperture of $f/5.6$ was used. The sensor resolution for experiments in the x and z directions was set to 1280×600.

Double-frame images were collected at a rate of 60 Hz. The image pre-processing procedure was the same as long-duration wall-normal measurements. Velocity vectors for the streamwise-spanwise field of view had a final IW size of 48×48 pixels (1.87×1.87 mm).

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The velocity vectors in the x, y and z directions are denoted by U, V and W, respectively. The symbol $\langle \ldots \rangle$ represents time averaging. The x component of the velocity vector at the centerline of the channel ($y = 0$) is denoted by U_c, while the streamwise velocity fluctuations are represented by u, which is calculated using the relationship $u = U - \langle U \rangle$. In order to obtain the wall shear rate $\dot{\gamma}_w$ for laminar cases, a parabolic function was fitted to the $\langle U \rangle$ versus y data, and the slope of the parabola at both wall locations was calculated and then averaged to determine $\dot{\gamma}_w$. For transitional and turbulent cases, a linear fit was applied to the $\langle U \rangle$ versus y data in the near-wall region of $y^+ \leq 5$ of both walls, and then to obtain $\dot{\gamma}_w$. With the wall shear rate determined, fluid viscosity at the wall shear rate (μ_w) was calculated for each test case using equation (1). The Reynolds number was then calculated as $Re = \rho U_B H / \mu_w$, where U_B is the bulk velocity and ρ is the fluid density. The wall shear stress (τ_w) was computed following $\tau_w = \mu_w \dot{\gamma}_w$, and this value was used to calculate the skin friction coefficient, $C_f = 2\tau_w / (\rho U_B^2)$. In the following sections, the superscript + denotes inner normalization, where velocity is normalized by the friction velocity $u_\tau = (\tau_w / \rho)^{1/2}$, and distance y is normalized by wall units $\lambda = \mu_w / \rho u_\tau$. For turbulent flows, the friction Reynolds number is defined as, $Re_\tau = \rho u_\tau h / \mu_w$.

3.5 Laminar/Turbulent Detection

The process of distinguishing between laminar and turbulent patches within transitional flow fields relied on the analysis of fluctuations in the centerline velocity, denoted as U_c. In order to eliminate the influence of high-amplitude, low-frequency

fluctuations that were present in visually laminar sections of the flow, a high-pass filter was initially applied to U_c. The cut-off frequency for this filter was set at $f_c = 0.05/T$. The outcome of this filtering process was a new filtered centerline velocity, referred to as u_f.

Subsequent to the filtering step, both a moving average and a moving standard deviation were calculated for u_f. This was achieved by employing a moving window with a length of $20T$, which allowed for a more detailed examination of the flow characteristics. In order to determine the nature of the flow within each moving window, a detection parameter I was introduced. This parameter was computed by taking the ratio between the standard deviation and the average value of u_f within each window.

The classification of flow as either turbulent or laminar was based on the value of the detection parameter I. Instances where I exceeded 0.02 were deemed turbulent, while those with lower values were considered laminar. It is important to note that any turbulent or laminar regions with a duration shorter than $20T$ were disregarded in this analysis, as they were deemed insufficiently representative.

Once the turbulent and laminar regions were identified, further analysis was conducted to quantify the turbulence characteristics. The turbulence fraction (F_T) was calculated by dividing the total duration of the turbulent flow by the overall acquisition time, providing insight into the prevalence of turbulence within the flow. In addition, the turbulence intensity (TI) for each region was determined by

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calculating the ratio of the standard deviation (σ) of the filtered velocity fluctuations to the mean velocity,

$$TI = \sigma/\langle U_c \rangle. \tag{3.3}$$

Figure 3.7 presents an example of the transitional water flow at $Re = 2000$, along with the application of the laminar/turbulent detection algorithm. The horizontal axis displays time, normalized by the representative time scale of the flow, denoted as $t' = t/T$. In Figure 3.7(a), the contour of streamwise velocity is depicted in relation to t', revealing alternating regions of turbulent patches and laminar flow. The extraction of the channel centerline velocity yields the signal displayed in Figure 3.7(b). Upon calculating the velocity fluctuations and applying the high-pass filter, the resulting signal, u_f, is illustrated in Figure 3.7(c). The high-pass filter effectively eliminates the low-frequency variations in U_c observed in visually laminar sections of the flow, specifically between t' values of 220 and 550 in Figure 3.7(a) and (b).

The detection parameter I is subsequently plotted in Figure 3.7(d). Laminar flow regions, characterized by $I < 0.02$, are represented by blue lines in the U_c, u_f, and I plots in Figure 3.7(b) through (d), while turbulent areas ($I > 0.02$) are indicated by red lines. A visual comparison of Figure 3.7(a) with the subsequent subplots demonstrates the detection algorithm's effectiveness in identifying the four turbulent patches present within the transitional water flow.
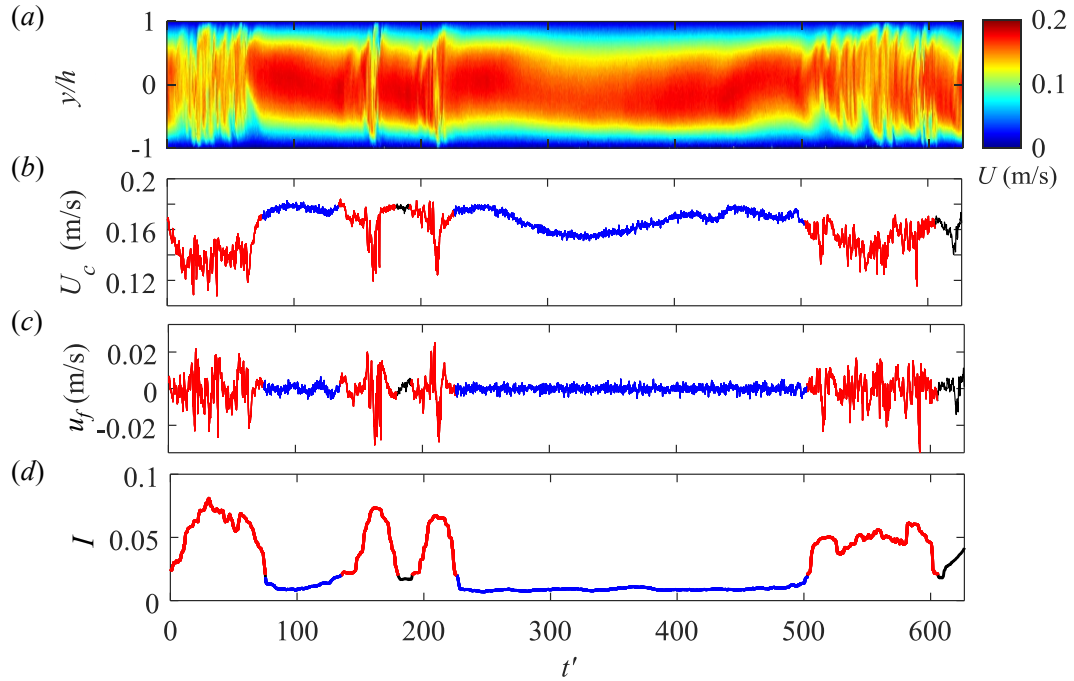
Figure 3.7 Laminar/turbulent identification technique of water flow. (*a*) a flow visualization contour, (*b*) the extracted centerline velocity signal, (*c*) filtered velocity fluctuations, (*d*) the detection parameter *I*. Turbulent regions are shown in red, laminar regions in blue, and short-length instances that are disregarded are in black.

3.6 Uncertainty Analysis

In this section, we will discuss the sources of uncertainty in our experiments. Uncertainties in particle image velocimetry measurements, shear viscosity measurements, and calculated parameters such as Reynolds number, friction factor, and inner-scaled velocity profiles are considered and presented. Understanding and quantifying these uncertainties is crucial for the accurate interpretation of our results and the reliability of our conclusions.

A frequently used approximation for the uncertainty linked to an individual PIV measurement is a displacement of 0.1 pixels. Sciacchitano (2019) argues that this "all-encompassing constant" for PIV uncertainty might be an oversimplification, as the uncertainty is largely influenced by the specific features of each experiment. Nevertheless, studies focused on assessing PIV uncertainty often report uncertainties close to 0.1 pixels (Raffel *et al.* 2018), which is why this value has been adopted in this work to represent the error associated with the PIV processing algorithm.

Shear viscosity measurements were conducted individually for each solution. Temperature variations have the potential to influence viscosity values; therefore, we carried out viscosity measurements at the same temperature as the experiments to minimize this impact. Inhomogeneities in the polymeric solutions or the presence of air bubbles may lead to errors in the viscosity measurements. To mitigate these effects, we ensured thorough sample preparation and degassing. Furthermore, each concentration was prepared and tested nine times. The standard deviation of these repetitions is presented in Figure 3.4.

The calculated parameters, such as Reynolds number, friction factor, and inner scaled velocity profiles, are derived from the PIV, shear viscosity measurements, and wall location. Wall location affects these parameters because it determines the boundary conditions for the fluid flow, which in turn influences the velocity gradients and shear stresses near the wall. As a result, the uncertainties in wall location measurements can impact the accuracy of the calculated parameters. Therefore, the uncertainties in these measurements propagate to the calculated parameters. Standard

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error propagation techniques were used to estimate the uncertainties in these parameters.

As mentioned before, Reynolds number was calculated as $Re = \rho U_B H / \mu_w$. Then the uncertainty in the Reynolds number (ΔRe) can be calculated using the formula for uncertainty propagation considering the uncertainty in fluid density is negligible,

$$\Delta Re = \sqrt{\left(\frac{\partial Re}{\partial U_B}\Delta U_B\right)^2 + \left(\frac{\partial Re}{\partial H}\Delta H\right)^2 + \left(\frac{\partial Re}{\partial \mu_w}\Delta \mu_w\right)^2}, \qquad (3.4)$$

where $\frac{\partial Re}{\partial U_B} = \frac{\rho H}{\mu_w}$, $\frac{\partial Re}{\partial H} = \frac{\rho U_B}{\mu_w}$, and $\frac{\partial Re}{\partial \mu_w} = -\frac{\rho U_B H}{\mu_w^2}$ are the partial derivatives of the Reynolds number with respect to independent variables and evaluated at the nominal values of the variables. In this context, the uncertainty associated with the channel height can be considered negligible. To calculate the relative uncertainty of the Reynolds number ($\Delta Re / Re$), the following formula is derived from equation (3.4),

$$\frac{\Delta Re}{Re} = \sqrt{(\frac{\Delta U_B}{U_B})^2 + (\frac{\Delta \mu_w}{\mu_w})^2}. \qquad (3.5)$$

Furthermore, as previously mentioned, the skin friction coefficient was determined using the formula $C_f = 2\tau_w / (\rho U_B^2)$. Employing a similar approach and assuming the uncertainty in fluid density to be negligible, the propagated error in the skin friction coefficient can be calculated as follows:

$$\Delta C_f = \sqrt{\left(\frac{\partial C_f}{\partial \tau_w}\Delta \tau_w\right)^2 + \left(\frac{\partial C_f}{\partial U_B}\Delta U_B\right)^2}, \qquad (3.6)$$

the relative uncertainty in skin friction factor ($\Delta C_f / C_f$) is calculated using the following formula,

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$$\frac{\Delta C_f}{C_f} = \sqrt{(\frac{\Delta \tau_w}{\tau_w})^2 + (2\frac{\Delta U_B}{U_B})^2}. \tag{3.7}$$

Since the wall shear stress is obtained as $\tau_w = \mu_w \dot{\gamma}_w$ and $\dot{\gamma}_w = \frac{du}{dy}$ at the wall location, the

uncertainty in wall shear stress ($\Delta \tau_w$) is calculated as,

$$\Delta \tau_w = \sqrt{\left(\frac{\partial \tau_w}{\partial y} \Delta y\right)^2 + \left(\frac{\partial \tau_w}{\partial \mu_w} \Delta \mu_w\right)^2}, \tag{3.8}$$

considering the partial derivatives to be derived as follows,

$$\frac{\partial}{\partial y}(\tau_w) = \mu_w \frac{\partial}{\partial y}\left(\frac{du}{dy}\right), \tag{3.9a}$$

$$\frac{\partial}{\partial u}(\tau_w) = \frac{\partial}{\partial u}\left(\mu_w \frac{du}{dy}\right) = \frac{\partial}{\partial u}\left(\frac{du}{dy}\right)\mu_w = 0, \tag{3.9b}$$

$$\frac{\partial}{\partial \mu_w}(\tau_w) = \frac{du}{dy}, \tag{3.9c}$$

the relative uncertainty in wall shear stress ($\Delta \tau_w / \tau_w$) could be derived as

$$\frac{\Delta \tau_w}{\tau_w} = \sqrt{(\frac{\Delta y}{y})^2 + (\frac{\Delta \mu_w}{\mu_w})^2}. \tag{3.10}$$

For inner scaled velocity (u^+), the error propagation will result in the following

uncertainty formula:

$$\Delta u^+ = \sqrt{\left(\frac{\partial u^+}{\partial u} \Delta u\right)^2 + \left(\frac{\partial u^+}{\partial u_\tau} \Delta u_\tau\right)^2}, \tag{3.11}$$

and the relative uncertainty in inner scaled velocity ($\Delta u^+ / u^+$) will be calculated as

$$\frac{\Delta u^+}{u^+} = \sqrt{(\frac{\Delta u}{u})^2 + (\frac{\Delta u_\tau}{u_\tau})^2}, \tag{3.12}$$

where relative uncertainty in friction velocity ($\Delta u_\tau / u_\tau$) is calculated as follows:

$$\frac{\Delta u_\tau}{u_\tau} = 1/2 \sqrt{(\frac{\Delta \tau_w}{\tau_w})^2 + (\frac{\Delta \rho}{\rho})^2}, \qquad (3.13)$$

and the uncertainty in solution density is deemed negligible.

The total relative uncertainty for the independent variables is presented in Table 5, while Table 6 displays the calculated total relative uncertainty for the aforementioned flow parameters in our experimental setup. In this context, $\langle U \rangle$ denotes the bulk velocity, μ_w represents the viscosity at the wall shear rate, Re signifies the Reynolds number, y denotes the wall-normal location, τ_w represents the wall shear stress, u_τ indicates the friction velocity, u^+ denotes the inner scaled velocity, and C_f refers to the skin friction coefficient.

Solution	$\dfrac{\Delta\langle U\rangle}{\langle U\rangle}$	$\dfrac{\Delta\mu_w}{\mu_w}$	$\dfrac{\Delta y}{y}$
Water	0.071%	2.0%	1.24%
50 ppm PAM	0.078%	2.6%	1.24%
75 ppm PAM	0.075%	2.9%	1.26%
100 ppm PAM	0.077%	2.9%	1.16%
150 ppm PAM	0.072%	4.9%	1.17%

Table 5 Estimated total uncertainties associated with independent flow variables.

Solution	$\dfrac{\Delta Re}{Re}$	$\dfrac{\Delta\tau_w}{\tau_w}$	$\dfrac{\Delta u_\tau}{u_\tau}$	$\dfrac{\Delta u^+}{u^+}$	$\dfrac{\Delta C_f}{C_f}$
Water	2.00%	2.35%	1.18%	1.18%	2.36%
50 ppm PAM	2.60%	2.88%	1.44%	1.44%	2.88%
75 ppm PAM	2.90%	3.16%	1.58%	1.58%	3.17%
100 ppm PAM	2.90%	3.12%	1.56%	1.56%	3.13%
150 ppm PAM	4.90%	4.93%	2.52%	2.52%	4.93%

Table 6 Estimated total uncertainties associated with calculated flow variables.

4. Results

The PIV measurements were utilized to investigate the transition from laminar to turbulent flow as the Re increased for both Newtonian fluids and PAM fluids. Initially, the velocity measurements were conducted for the Newtonian case involving water. Subsequently, the PIV measurements were performed for PAM solutions with low concentrations, specifically at $c = 50$ and 75 ppm. Following that, the measurements were conducted for high-concentration PAM solutions with $c = 100$ and 150 ppm. To account for differences in rheology and the transition from laminar to turbulent behaviour, the results for low and high-concentration PAM solutions were separately presented. Each section showcases the variations in C_f and F_T as the Reynolds number increases. Additionally, instantaneous samples of U were captured along the streamwise-wall-normal and streamwise-spanwise planes at different Reynolds numbers, exhibiting characteristics of laminar, transitional, and turbulent flow fields as indicated by their corresponding F_T values.

4.1 Transition in Newtonian channel flow

Figure 4.1 illustrates the relationship between the skin friction coefficient, C_f and Reynolds number, Re for water channel flows. Each distinct cluster of data points, represented by different colours, corresponds to specific valve openings discussed in section chapter 3. The legend of Figure 4.1 provides the nominal Reynolds number for each valve opening. To ensure utmost accuracy and reliability, each valve opening was meticulously repeated six times, accompanied by the acquisition of long-duration double-frame data. This comprehensive approach aimed to achieve improved statistical convergence, especially in transitional flows characterized by sporadic intermittent turbulent patches.

For turbulent flows at higher Re the statistical convergence becomes less crucial. As a result, three repetitions of short-duration time-resolved measurements were performed for each valve setting with higher Re. The corresponding data, represented by hollow markers, are displayed in Figure 4.1. In contrast, the filled markers indicate the results obtained from long-duration double-frame measurements. The measured values of the skin friction coefficient are presented in conjunction with theoretical expectations for both laminar and turbulent channel flows. Specifically, for laminar flows, the expected relationship is $C_f = 12/Re$, while the power-law correlation proposed by Dean (1978), $C_f = 0.073\,Re^{-1/4}$, represents the turbulent flows. To provide a baseline comparison, measurements of C_f from the channel flow experiments conducted by Patel & Head (1969) in high aspect ratio channels between Re values of

1000 and 7000 are also included in Figure 4.1, represented by gray markers. Each marker corresponds to a specific data point extracted from the experiments conducted by Patel & Head (1969), and the corresponding C_f and Re values have been digitized and recorded for reference.

At the lowest measured nominal Re of 1470, values of C_f agree well with the theoretical C_f line for laminar flows and the experimental results of Patel & Head (1969). As the nominal Re increases to 1930, the data points overlap with the experimental results of Patel & Head (1969). The repeated measurements show good agreement with one another within the estimated measurement uncertainty. As the nominal Re continues to increase, C_f gradually approaches the Dean (1978) equation for turbulent flows, indicating that the flow is becoming turbulent. Measurements of C_f acquired from short-time data collections form a cluster with a nominal Re of 2930 that still agrees with the results of Patel & Head (1969) and is slightly below the approaches the Dean (1978) equation for turbulent flows. As the nominal Re continues to increase beyond 3510 the measurements lie close to the empirical correlation of Dean's (1978). This implies that the measurements of C_f as a function of Re of water show good agreement with empirical Newtonian expectations in laminar and turbulent regimes, and reasonable conformance with previous experimental measurements of Newtonian transition in channel flows.

Iida & Nagano (1998) carried out a DNS investigation of turbulent channel flows. They decreased the Reynolds number to transitional values and studied relaminarization and turbulence statistics. They observed in the case of a decrease in

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friction Reynolds number from $Re_\tau = 80$ to 60, a quasi-laminar state appears in which the skin friction coefficient C_f is observed to be in between the laminar and turbulent values. This quasi-laminar state is characterized by a balance between Reynolds shear stresses and the collapse of the standard logarithmic law. The presence of the quasi-laminar state explains why C_f does not suddenly increase from the laminar to the turbulent values, but rather shows a gradual departure from laminar values and a gradual approach to turbulent values. Patel & Head (1969) and Jones (1976) observed the gradual deviation of the C_f value from the theoretical laminar values and its slow convergence towards the anticipated turbulent values. However, neither of these studies provided an explanation for this phenomenon.

The investigation by Yimprasert et al. (2021) delves into the transition from laminar to turbulent flow within a channel, with a particular emphasis on the evolution of the skin friction coefficient. Their experimental data adhered to the theoretical laminar line for low Re, but began to diverge at approximately $Re = 1250$, reaching a local maximum at $Re = 1900$. They further observed that the flow approached full turbulence for $Re \geq 2600$. Importantly, their skin friction values for $Re > 2000$ were found to be in alignment with previous experimental and DNS results. However, they noted a discrepancy where their estimated skin friction deviated from the laminar line later than the skin friction measurements, suggesting that the non-turbulent region may not be purely laminar. Their attempts to model skin friction in the transitional region, based on intermittency and laminar and turbulent skin friction values, yielded lower values than those obtained experimentally. This suggests that regions of laminar

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flow in close proximity to turbulent patches exhibit higher skin friction than those of undisturbed laminar flow.
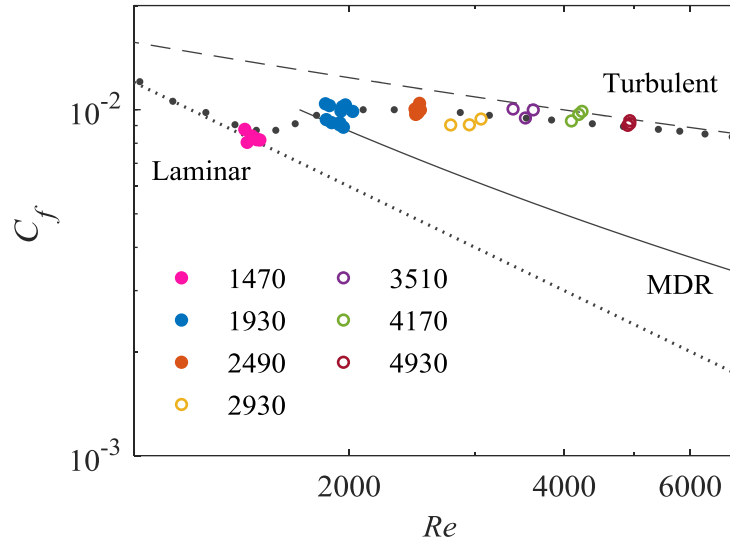
Figure 4.1 Skin friction factor (C_f) is plotted versus Reynolds number. The Patel & Head (1969) data is reproduced from their channel flow data. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements. The figure legend illustrates the nominal Re for each valve setting

Figure 4.2 illustrates the percentage of turbulence, F_T, observed in the Newtonian flow of water. In accordance with the methodology outlined in section 3.5, F_T is determined as the proportion of time during which the flow is considered turbulent. At the nominal Re of 1470, measurements of six repeated tests show F_T values of zero implying the flow is laminar. Transitional flow features ($F_T > 0$) are observed at measurements with $Re = 1948$, 1957 and 1913. At a slightly larger Re of 2200, the

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flow becomes turbulent with $F_T = 1$. Beyond, Re of 2490 all flows are turbulent. The rapid transition process is evident based on the data points with the nominal Re of 1930 and a wide margin of F_T values between 0.41 and 0.84. These data points that fall between laminar and turbulent values of F_T in Figure 4.2 are scattered due to this rapid variation in the flow state and intermittency in the transitional flow. The abundance of turbulent patches and the amount of intermittency is not consistent among flows of the same nominal Re as they exhibit a wide range in F_T between 0 and 1. Assuming the transition Re band for water flow is 465 starting from $Re = 1500$ up to $Re = 1965$ and the critical Re of 1930 our observations agree with Patel & Head (1969) investigation that observed intermittency in the range of $1380 \leq Re \leq 1800$.

Sano & Tamai (2016) estimated a comparable parameter by quantifying the temporal fraction occupied by turbulent flow over an extended period of time. They conducted experiments at various downstream positions of a channel flow and observed that the transitional region commenced, i.e., the turbulence fraction increased from zero, at a Re of 1070. The authors derived the turbulence fraction using a flow visualization technique. However, their detection algorithm employed a simple binarization method with a minimal threshold, which may have potentially identified fluctuations unrelated to small-scale turbulence, leading to a lower Re for the onset of intermittency.

Another relevant parameter is the intermittency factor (Rotta 1956), which serves as a quantification of transitional flow fields encompassing both laminar and turbulent components. The intermittency factor is determined by calculating the ratio of the

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total duration of turbulence to the overall duration. Rotta (1956) noted that in pipe flows, the occurrence of intermittency is observed within the range of Reynolds numbers approximately between 2200 and 2800. Seki & Matsubara (2012) devised a novel approach for determining the intermittency factor in channel flow, eliminating the requirement for a threshold value. Their investigation revealed that the lowest Reynolds number for fully developed turbulent flow is 2600, whereas the lower marginal *Re*, also referred to as the transition Reynolds number, is 1400. This finding aligns with our own observations of intermittency using the turbulent fraction. In general, our F_T data exhibits a consistent pattern of escalating turbulence fraction as the *Re* increases, corroborating earlier experimental studies.
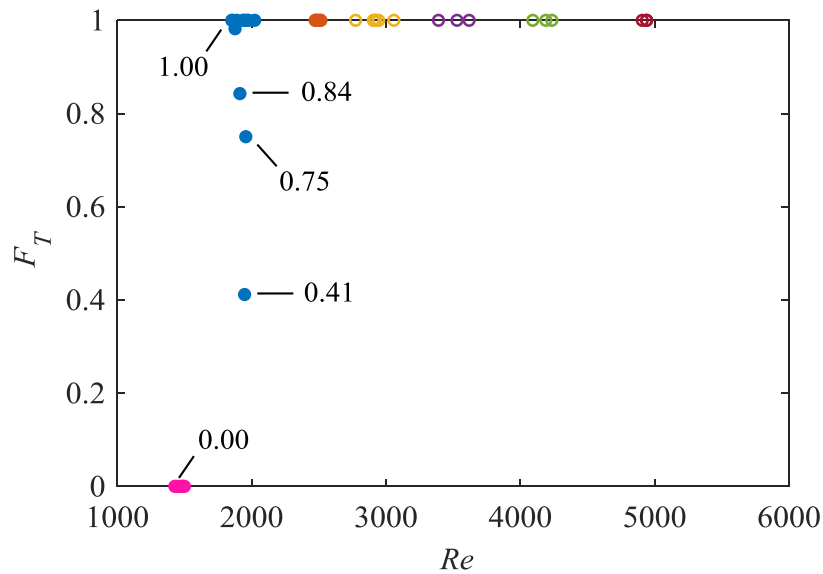
Figure 4.2 The turbulent fraction (F_T) for water is shown as a function of the Reynolds number. The annotation shows the F_T values for data points selected for further analysis in the subsequent figures.

Sample measurements of U normalized by the mean centreline velocity $\langle U_c \rangle$ along the streamwise-wall-normal plane are shown in Figure 4.3 for different channel flows of water at $Re = 1400$ with $F_T = 0$, $Re = 1865$ with $F_T = 0.68$ and $Re = 1965$ with $F_T = 1$. The flow is moving from left to right here and the horizontal axis is the non-dimensionalized time t'. The vertical axis is the wall-normal position y normalized by channel half-height h.

For Figure 4.3(a) the turbulence intensity TI along the centreline of the flow is calculated to be as low as 1% based on equation (3.3). Figure 4.3(b) displays the transitional flow of the water experiment. The TI for the laminar section of this flow is calculated to be 1.2% and for the turbulent part, it is calculated to be 5.5%. Durst et $al.$ (1998) conducted measurements of turbulence intensity in water channel flow during the laminar to turbulent transition. Their observations revealed that turbulence intensity remained below 2% up to Re of 2000. However, as Re increased to 4000, turbulence intensity surged and then reached a plateau at 4% for fully turbulent flows above $Re = 8000$. At small t', the flow starts in a laminar state, then two turbulent spots emerge at t' of 130 and 220. The spots are confined by laminar regions and show abrupt changes in the velocity field. Moreover, the flow inside turbulent spots exhibits characteristics of fully turbulent flow with fluctuations that span the full channel height. These characteristics are consistent with the study of flow within turbulent spots previously investigated by Lemoult et $al.$ (2014). Their study involved the generation of turbulent spots by introducing perturbations into a pressure-driven channel flow with an aspect ratio of 15 and Re of 1500. They investigated the spot

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structure and flow around it. The shorter turbulent spots are followed by a turbulent

region which lasts over 150 time units between t' of 300 to 430. After this turbulent

region, the flow returns to a laminar state from t' of 430 to 500. Figure 4.3(*c*) displays

the turbulent flow state in water at $Re = 1965$, where chaotic behaviour is observed

and continuous variation in U can be noticed at all values of y/h and t'. The TI value

for this flow is calculated to be 5.5%.
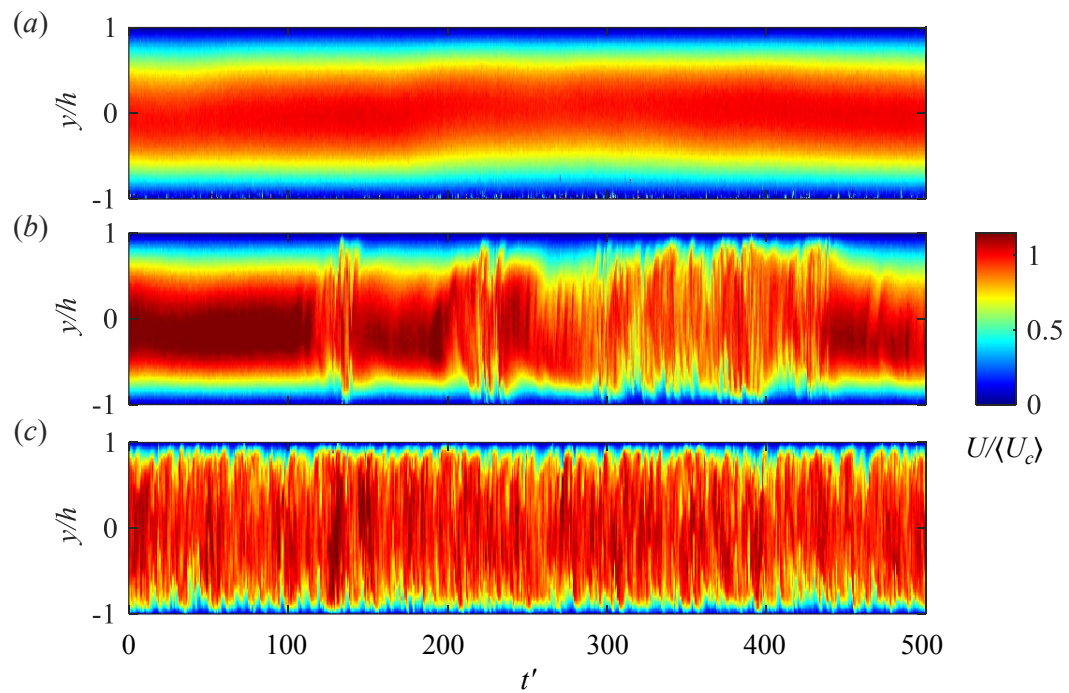
Figure 4.3 Spatial contours of normalized streamwise velocity ($U/\langle U_c \rangle$) from streamwise-wall-normal measurements presenting (*a*) laminar, (*b*) transitional with $F_T = 0.41$ and (*c*) turbulent flow fields for water. The Reynolds number is 1400, 1870 and 2550, respectively.

The contours of $U/\langle U_c \rangle$ along the streamwise-spanwise plane at $y = 0$ for laminar, transitional and turbulent flows of water are shown in Figure 4.4. In order to keep consistency with streamwise-wall-normal results, $\langle U_c \rangle$ is calculated along $z = 0$ for streamwise-spanwise results. Similar to Figure 4.3, the horizontal axis is t', however, the vertical axes now correspond to the spanwise position z normalized by h. In Figure 4.4(a) there is some evidence of low-frequency streamwise streaks. However, along $z = 0$, TI is low and approximately equal to 1.2%, which agrees well with the laminar TI from wall-normal results. Furthermore, Figure 4.4(a) does not show the chaotic mixing behaviour commonly seen in turbulent flows. Seki & Matsubara (2012) noted that the velocity fluctuation in the upstream flow of high Reynolds number laminar cases possessed sufficiently high and broad spectral components. These served as the upstream disturbance for their experiment. A particular point of interest was the identification of a low-frequency peak. According to the previous flow visualizations conducted by their research group (2011; 2006), this scale is larger than the turbulent disturbance scale, yet smaller than that of the turbulent patch passing. The low-frequency events observed in Figure 4.4(a) could potentially be attributed to the observations made by Seki & Matsubara (2012). Considering the $\langle U_c \rangle = 0.134$ m/s for the flow field shown in Figure 4.4(a) and comparing it to a flow with a similar valve opening measured along the streamwise-wall-normal plane from Figure 4.3(a) with $\langle U_c \rangle = 0.133$ m/s, it can be concluded that the Re for Figure 4.4(a) should be close to 1470. Figure 4.4(b) shows measurements of $U/\langle U_c \rangle$ along the streamwise-spanwise plane for a transitional flow of water. Between t' of 0 and 100, a turbulent region

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passes, followed by elongated low-speed streaks connected to its trailing edge. The instability starts again at the t' of 350, and a turbulent spot emerges at t' of approximately 450. The observed turbulent spot is connected to a low-speed streak in its leading point and has oblique fronts between the core turbulent region and surrounding laminar flow on its sides. The Re of a flow with a similar valve opening measured along the streamwise-wall-normal plane is approximately 1930. These observations agree well with flow visualizations conducted by Carlson *et al.* (1982), who demonstrated that the turbulent spots in channel flows have a distinct arrowhead shape. Moreover, in contrast to the hairpin-dominated spots observed in boundary layers (Schröder *et al.* 2008), channel spots are characterized by semiregular streamwise streaks accompanied by localized chaotic eddies (Wu 2023). Another noteworthy feature of channel spots is the presence of oblique wave packets emanating from the spanwise wingtips observed by Henningson & Kim (1991). Lemoult *et al.* (2014) also discovered the travelling-wave-like structures near the trailing edge of a turbulent spot. Similar structures are observed in Figure 4.4(*b*) from $t' = 350$ up to $t' = 450$. Consequently, channel flow spots consist of three distinct regions: a central turbulent eddy region, a wingtip wave region, and a streamwise streak region. Figure 4.4(*c*) displays $U/\langle U_c \rangle$ for a turbulent flow of water. As expected, the turbulent state demonstrates a fully chaotic behaviour that extends fully along the measured domain of z. A flow with a similar valve opening measured along the streamwise-wall-normal plane has $Re = 2490$.
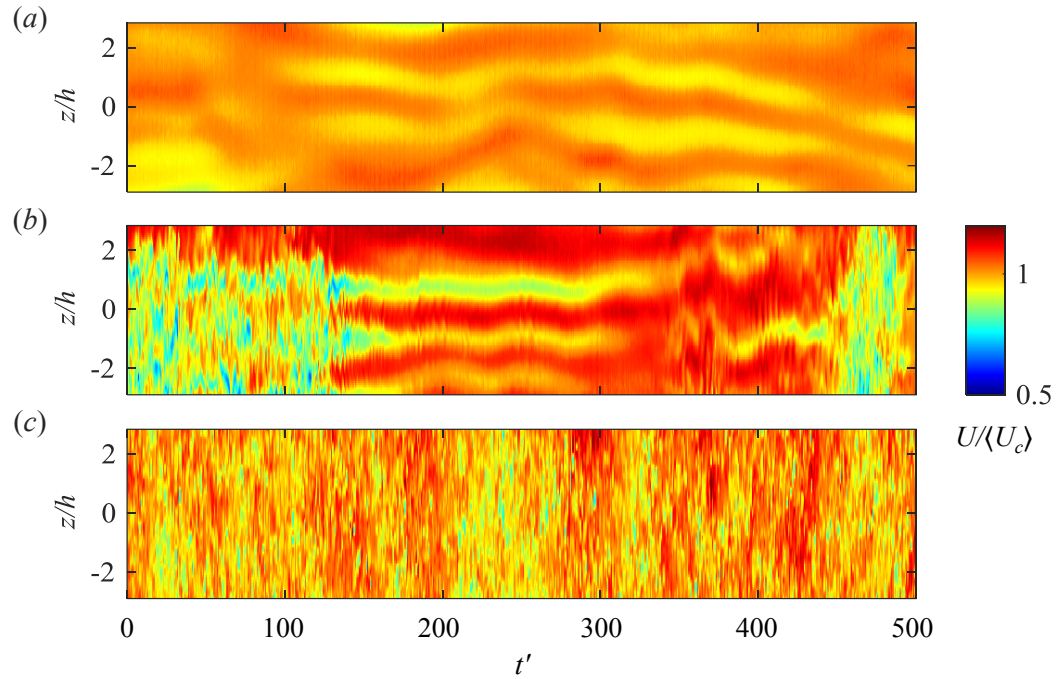
Figure 4.4 Spatial contours of normalized streamwise velocity, $U/\langle U_c \rangle$, from streamwise-spanwise PIV measurements showing (*a*) laminar, $Re \approx 1470$, (*b*) transitional, $Re \approx 1930$ and (*c*) turbulent, $Re \approx 2490$ flow fields for water experiments.

Figure 4.5(*a*) shows outer-scaled velocity profiles of water flows for five different values of F_T. This figure also shows the theoretical parabolic velocity profile for laminar flows and a mean velocity profile derived from direct numerical simulation (DNS) of Iwamoto *et al.* (2002) for a turbulent Newtonian channel flow at low $Re_\tau = 110$. Due to the intermittent nature of transitional flow fields, their velocity profiles exhibit asymmetry, and the maximum streamwise velocity value across the channel height may not occur at the channel centerline. Therefore, the mean streamwise velocity $\langle U \rangle$ is normalized using the maximum velocity across the channel, U_0, instead

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of centerline velocity U_c. The cases shown in Figure 4.5 correspond to the flow cases with F_T values specified in Figure 4.2. As seen in Figure 4.5(*a*), measurements of $\langle U \rangle / U_0$ for the laminar flow of water with an $F_T = 0$ and $Re = 1460$, agree well with the theoretical parabolic velocity profile. As F_T increases, the velocity profiles begin to deviate from the Poiseuille laminar trend, and have profiles of $\langle U \rangle / U_0$ that fall between the laminar and turbulent profiles. The velocity profiles falling between the laminar and turbulent profiles can be explained by the intermittency of the flow, which shows periods of laminar and turbulent behaviour. Intermittency refers to the coexistence of laminar and turbulent domains in some range of flow conditions. Despite the long data acquisition time, the transitional velocity profiles are still prone to asymmetry. This suggests that turbulent spots within the transitional flows occur at low frequencies and longer acquisition times are still needed to obtain better statistical convergence in $\langle U \rangle$ for the transitional flows. Finally, measurements of $\langle U \rangle$ for the turbulent flow of water with $Re = 1850$ (equivalent to $Re_\tau = 90$) agree well with the DNS from (Iwamoto *et al.* 2002) at $Re_\tau = 110$. Overall, the measurements of $\langle U \rangle / U_0$ shown in Figure 4.5(*a*) are consistent with expectations for a Newtonian channel flow undergoing laminar to turbulent transition.

In Figure 4.5(*b*), inner-normalized profiles of $\langle U \rangle^+$ versus y^+ for the same water flows detailed in Figure 4.5(*a*) are demonstrated. Dashed lines show $\langle U \rangle^+ = y^+$ for the viscous sublayer and the logarithmic law of the wall, $\langle U \rangle^+ = 2.44 \ln y^+ + 5.5$ for the logarithmic layer. In order to generate inner-normalized velocity profiles, the velocity profiles were subjected to averaging in the vicinity of the channel centerline ($y = 0$).

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This procedure ensures the attainment of symmetric velocity profiles, even in cases exhibiting asymmetry. Subsequently, the inner-scaled velocity profiles were derived by utilizing the aforementioned averaged velocity profiles. Figure 4.5(b) indicates that the laminar flow has the largest positive offset relative to the logarithmic law of the wall. As F_T increases, $\langle U \rangle^+$ gets closer to the logarithmic law of the wall. This indicates that the turbulent flow is more closely aligned with the expected logarithmic profile near the wall. However, as seen in Iwamoto (2002), turbulent flow at a low Re_τ of 110 is not expected to perfectly follow the logarithmic law of the wall. Our experiments also show this phenomenon for the case at $Re = 1850$ with $F_T=1$, with the turbulent velocity profiles deviating from the logarithmic law of the wall at low Reynolds numbers.

The mean dynamics of channel flow in the transitional state were investigated by Elsnab et $al.$ (2011). They observed in the transitional regime, the mean velocity profiles gradually flatten with increasing Reynolds number. The shape of the profiles they acquired are similar to that reported by Orszag & Kells (1980) for laminar channel flow perturbed by finite amplitude two and three-dimensional Orr-Sommerfeld eigenfunctions. Furthermore, Elsnab et $al.$ (2011) observed when plotted on semi-logarithmic axes, all of the inner-normalized mean profile measurements converge onto a single curve for $y^+ \lesssim 15$. However, these profiles deviate slightly from the linear viscous sublayer. Moreover, at $y^+ > 30$, the higher Reynolds number profiles exhibit a logarithmic-like dependence.
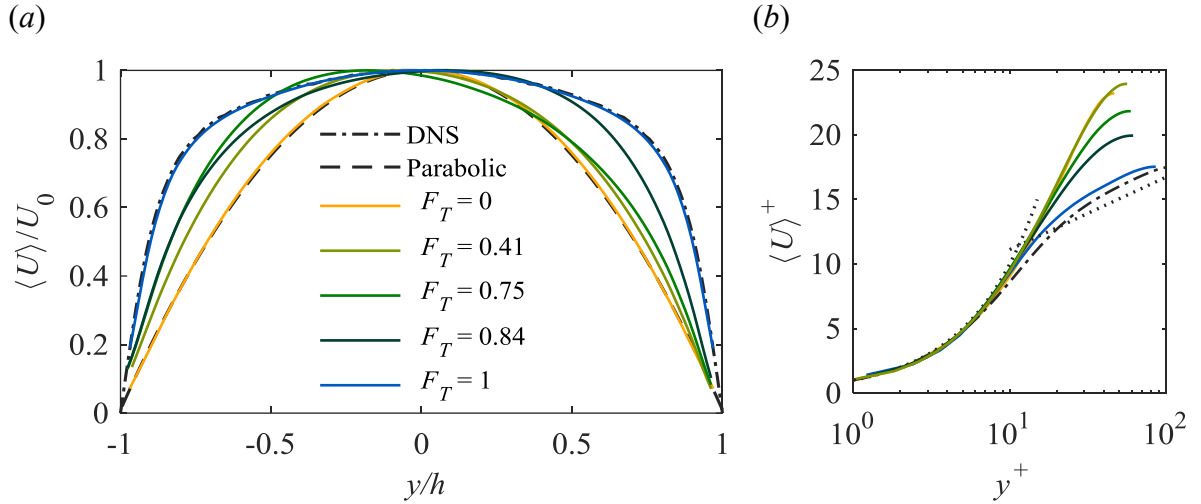
Figure 4.5 The velocity profiles for various turbulent fractions of water flow are illustrated in (*a*) outer scaling and (*b*) inner scaling. Reynolds numbers in order of increasing F_T are: 1460, 1950, 1960, 1910, 1850. The DNS is from Iwamoto (2002), and the parabolic function is the theoretical velocity profile for laminar channel flows. The dotted lines show the viscous sublayer and logarithmic law of the wall.

4.2 Transition for low-concentration PAM solutions

Figure 4.6 and Figure 4.7 displays C_f versus Re for the 50 and 75 ppm solutions of PAM respectively. The maximum drag reduction (MDR) asymptote shown with solid line follows $C_f^{1/2} = 19 \log_{10}(Re\ C_f^{1/2}) - 32.4$ (Virk et *al.* 1970).

For the 50 ppm PAM solution, time-resolved data acquisition was employed to collect data at two valve settings with low Re and three valve settings with higher Re values beyond the transitional range. Data at two valve settings within the transitional Re zone were gathered using the long-duration double-frame system. The lowest nominal Re of 1080 has C_f values that overlap with the theoretical laminar value $C_f = 12/Re$. With a further increase of nominal Re to 1590, it can be observed that values of C_f continue to follow the laminar trend and deviate from the Newtonian transition

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seen from Patel & Head (1969). At the nominal Re of approximately 2070 measurements of C_f are scattered, indicating the presence of a transitional flow. The data points lie between the Newtonian laminar and turbulent trends, marking the start of drag reduction. The scatter in the data points continues also at $Re = 2460$. At nominal Re of 2780, the data attain values of C_f higher than MDR but lower than the Newtonian turbulent trend. With rising the nominal Re to values of 3310 and 3710, two clusters of data points show a decreasing trend in skin friction coefficient below Patel & Head (1969) values.
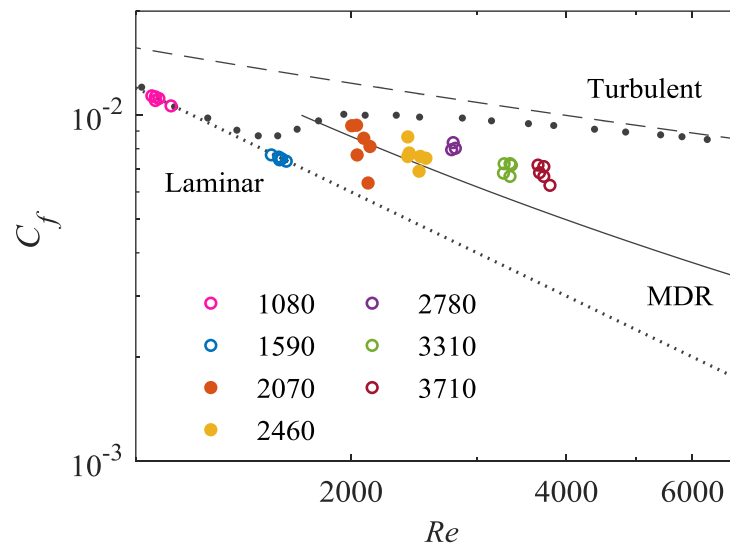
Figure 4.6 Skin friction factor (C_f) plotted as a function of the Reynolds number for 50 ppm solutions of PAM. Patel & Head (1969) data is shown as grey filled circles. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements.

For PAM solutions with a c of 75 ppm, the measurements of C_f at the nominal Re of 1290 fall on the laminar trend, as shown in Figure 4.7. At the nominal Re of 1750, the data points start to deviate from the theoretical laminar trend and become slightly scattered. With an increase in the nominal Re to 2080, repeated measurements show a range of different C_f values that fall between the laminar and MDR lines, indicating a transitional state. Increasing the Re to 2800, the C_f grows to a value relatively close to Patel & Head (1969). Increasing nominal Re further to 3210 and 3570, the next two clusters of C_f measurements show a descending trend toward MDR asymptote and well below the experimental measurements of Patel & Head (1969). The data shows that the C_f exhibited a clear relationship with Re beyond a specific onset point of Re = 2780 for 50 ppm and Re = 2740 for 75 ppm. The slope in C_f reduction with increasing Re differs from the turbulent friction factor correlation proposed by Dean (1978) This finding aligns with the type A behaviour discussed in Virk & Wagger (1990). In type A drag reduction, a distinct onset point for drag reduction can be identified. Prior to this point, the C_f increases with Re; however, once the drag reduction initiates, it demonstrates a proportional increase with Re. In other words, C_f values decrease at a higher rate with increasing Re compared to the C_f-Re trend for water flow. Concerning the transition from laminar to turbulent flow, type A drag reduction exhibits a transition to turbulence, accompanied by an increase in C_f. Subsequently, after drag reduction onset, as Re values continue to rise, C_f will decrease and skin friction values will approach the MDR values from above.

Overall, measurements of C_f as a function of Re are different from the results of water, shown in Figure 4.1, and the previous experimental data for Newtonian channel flows reported by Patel & Head (1969). Our measurements show that at certain Re, the skin friction factor values fall between the laminar and turbulent trends, and there is a positive relationship between drag reduction and Reynolds number beyond the onset point.
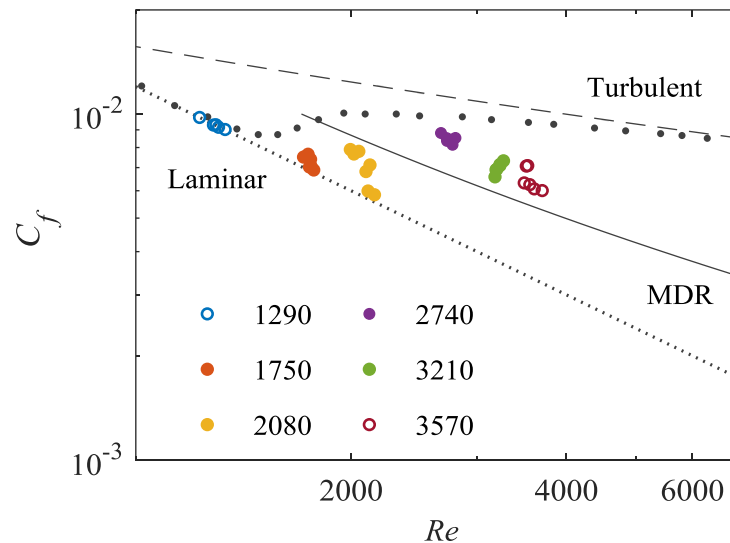
Figure 4.7 Skin friction factor (C_f) plotted as a function of the Reynolds number for 75 ppm solutions of PAM. Patel & Head (1969) data is shown as grey filled circles. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements.

The turbulent fraction F_T with respect to Re is shown in Figure 4.8 for the 50 ppm PAM solution. Flows of the 50 ppm solutions at nominal Re of 1080 and 1590 have F_T values equal to zero and are therefore, laminar. At the nominal Re of 2070, six

repeats of measurements show a wide range of F_T values between 0.1 and 1.0. This wide range of F_T values at an approximately constant Re demonstrates how turbulence can arise suddenly in a narrow Re band for the 50 ppm PAM solution. Increasing the nominal Re further to values greater than or equal to 2460 produces chaotic flows that generally have an F_T of 1.0.
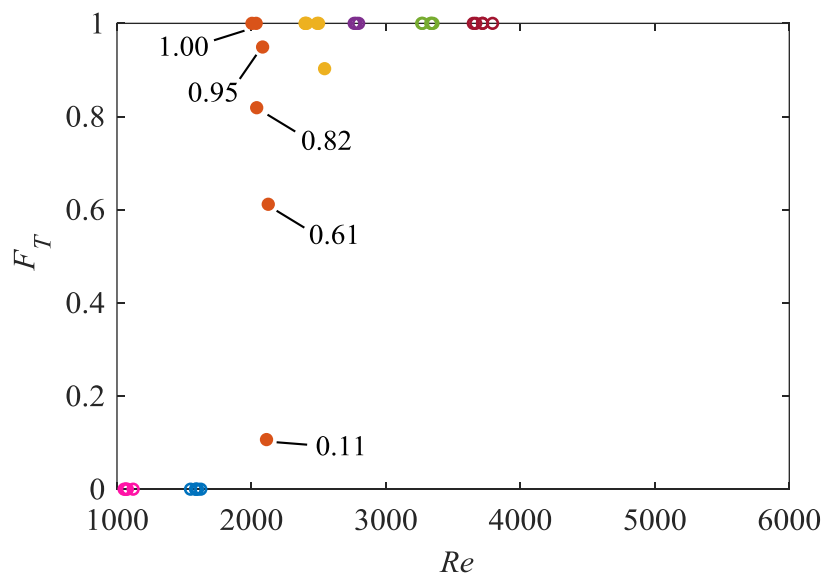
Figure 4.8 The turbulent fraction (F_T) for 50 ppm solutions of PAM is shown versus the Reynolds number. Colours show nominal Re same as Figure 4.6. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements. The velocity profiles for data points with annotated F_T will be illustrated.

Figure 4.9 demonstrates values of F_T versus Re for the 75 ppm flows. At nominal Re of 1290, all measurements reflect laminar conditions with values of F_T equal to 0. Transition to an intermittent condition sets in at nominal Re of 1750 with variations

in F_T that range from 0 to 0.44. The laminar-turbulent intermittency continues at nominal Re of 2080 with measurements showing a wide range of F_T from 0 to 0.73. Finally, for all measurements above Re of 2740, the flow is chaotic with all measurements of F_T being equal to 1.

Together, Figure 4.8 and Figure 4.9 show that the onset of turbulence in the low-concentration polymer flows is delayed slightly to $Re = 2070$ and $Re = 2080$ for 50 ppm and 75 ppm solutions, respectively, compared to the Newtonian flows with transition Re of 1930 detailed in Figure 4.2. This is in line with the theory of Samanta *et al.* (2013) and other investigations (Draad *et al.* 1998; Escudier *et al.* 1998; Giles & Pettit 1967; Pinho & Whitelaw 1990), that flexible polymers suppress Newtonian turbulence and delay the transition. Furthermore, the transitional Re band (the difference between the highest Re with $F_T = 0$ and lowest Re with $F_T = 1$) covers a wider range of Re as the polymers are introduced to flow. Compared to the 465 transitional Re band for water, 50 ppm solution shows 1045 and 75 ppm shows 1005 transitional Re band.
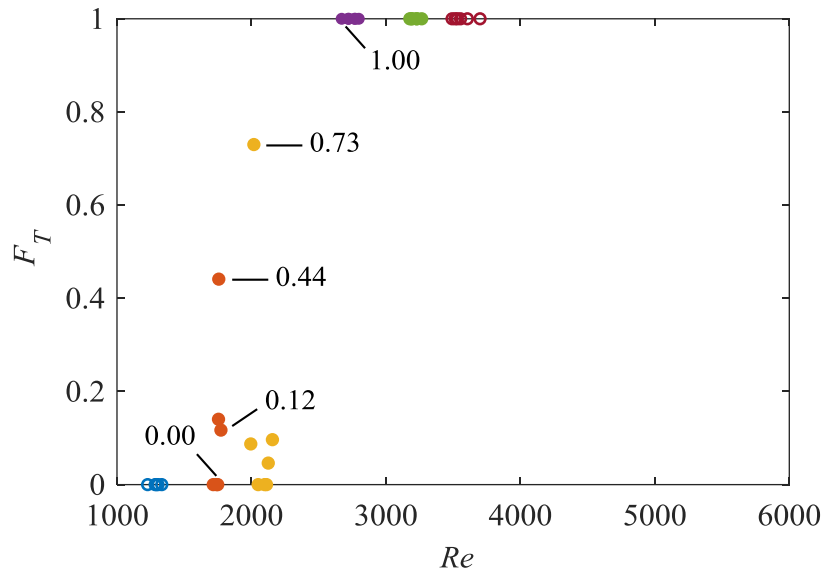
Figure 4.9 The turbulent fraction (F_T) for 75 ppm solutions of PAM is shown versus the Reynolds number. Colours show nominal Re same as Figure 4.7. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements. The velocity profiles for data points with annotated F_T will be illustrated.

Figure 4.10 demonstrates the contours of $U/\langle U_c \rangle$ measured along the streamwise-wall-normal plane of the PAM solutions with different values of F_T. Figure 4.10(a) demonstrates the laminar flow of the 75 ppm solution, with an $F_T = 0$ at $Re = 1720$. As expected, the flow is visually steady and does not show any significant variations of $U/\langle U_c \rangle$ over t'. Turbulence intensity for this case is measured to be 1.1%. Figure 4.10(b) displays $U/\langle U_c \rangle$ for the 50 ppm solution in a transitional state, with an F_T value of 0.61 and $Re = 2125$. This transitional flow exhibits several turbulent spots interspersed between laminar regions. The turbulence observed in low concertation solutions appears to be similar to the Newtonian turbulent spot shown in Figure 4.3(b).

Lastly, Figure 4.10(*c*) demonstrates $U/\langle U_c \rangle$ for the 75 ppm PAM solution in a turbulent state and at $Re = 2670$. Despite having a lower C_f than Newtonian turbulence – demonstrated by Figure 4.6– the spatial patterns of $U/\langle U_c \rangle$ are visually similar to water with an F_T of 1 seen in Figure 4.3(*c*). Specifically, both flows are disordered for all instances of t', with no apparent regions of calm laminar flow seen previously in Figure 4.3(*b*) and Figure 4.10(*b*).
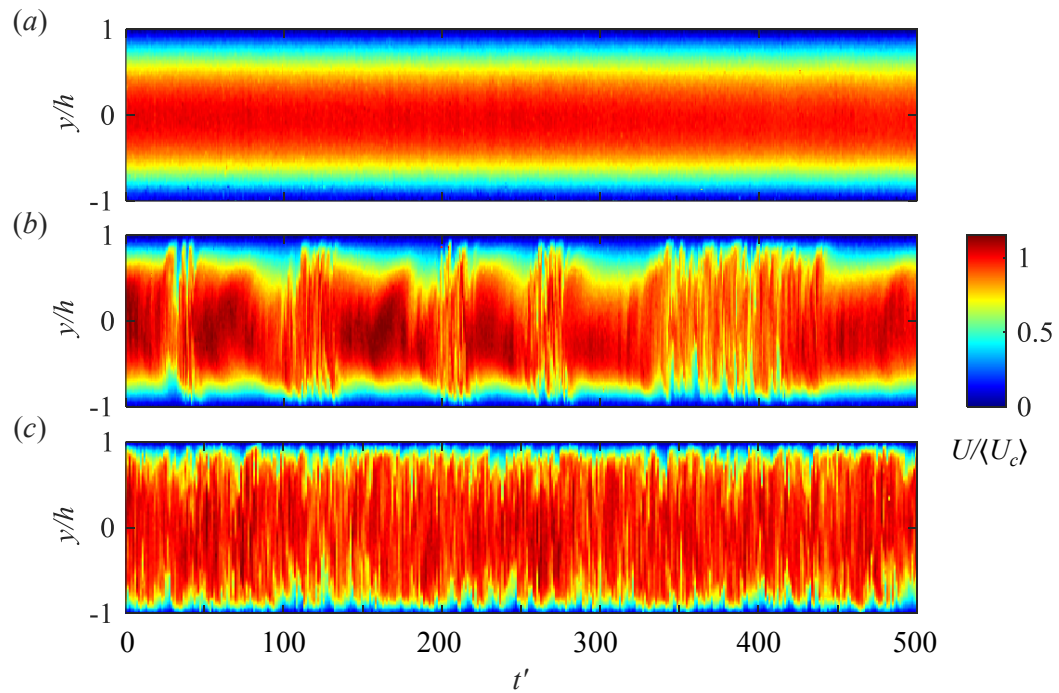
Figure 4.10 Spatial contours of normalized streamwise velocity ($U/\langle U_c \rangle$) from streamwise wall-normal measurements of three different flow states of low-concentration PAM solutions (*a*) 75 ppm laminar, $Re = 1720$, (*b*) 50 ppm, $F_T = 0.61$, $Re = 2125$, (*c*) 75 ppm turbulent, $Re = 2670$.

In Figure 4.11, contours of $U/\langle U_c \rangle$ along the streamwise-spanwise plane are shown for flows with different values of F_T. In Figure 4.11(a), the laminar flow with an $F_T = 0$ at $Re = 1750$ does not show any considerable variation in $U/\langle U_c \rangle$. The turbulence intensity of this case has been measured to be 1%. However, for the transitional case shown in Figure 4.11(b) with $Re \approx 2080$, variations in $U/\langle U_c \rangle$ along z and t' are present. Elongated streaks of low $U/\langle U_c \rangle$ are observed between $t' = 0$ and 200. Beyond $t' = 200$, the streamwise streaks become increasingly chaotic and exhibit fluctuations in $U/\langle U_c \rangle$ that span the complete measurements domain along z. The chaotic region is extended to $t' = 450$, after which the flow recovers to a relatively, calm and laminar state. The central turbulent eddy region within this chaotic structure bears a resemblance to turbulent spots observed in Newtonian flows (Wu 2023), albeit lacking the distinctive arrowhead shape. Instead, the leading edge of this chaotic structure is connected to streamwise streaks, and the instability persists into the turbulent eddy core. Lastly, Figure 4.11(c) shows the chaotic flow of PAM with $c = 75$ ppm and $F_T = 1$ at $Re = 3210$. Comparing Figure 4.11(c) to the streamwise-spanwise plane measurements of water in Figure 4.4(c) demonstrates that the drag-reduced chaotic state is not visually different from pure Newtonian turbulence.
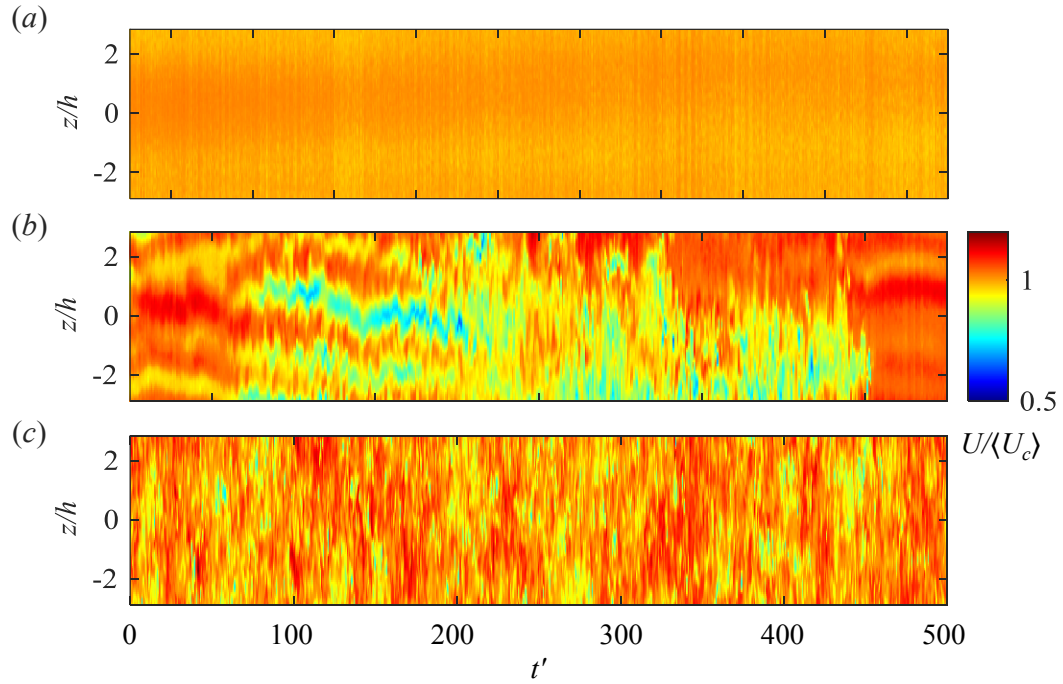
Figure 4.11 Spatial contours of normalized streamwise velocity, $U/\langle U_c \rangle$, from streamwise spanwise measurements for (*a*) laminar $Re \approx 1750$, (*b*) transitional $Re \approx 2080$ and (*c*) turbulent flows $Re \approx 3210$ in 75ppm solution.

In Figure 4.12(*a*) and (*b*), the mean streamwise velocity normalized by the average maximum velocity across the channel, $\langle U \rangle / U_0$, is plotted with respect to y/h for the 50 and 75 ppm PAM solutions. Similar to the Newtonian transitional flows shown in Figure 4.5(*a*), transitional flow conditions of low-concentration PAM flows with $0 < F_T < 1$, also have an asymmetric velocity profile about $y = 0$. On the other hand, laminar flows with F_T values equal to 0, and turbulent flows with F_T of 1, are symmetric about $y = 0$. Additionally, we see that the velocity profiles become blunt with increasing F_T values, similar to what was previously observed in the Newtonian case shown in Figure 4.5(*a*).

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Figure 4.12(c) and (d) demonstrate the inner-scaled velocity profiles for low-concentration PAM solutions with c = 50 and 75 ppm. The MDR velocity profile $\langle U \rangle^+$ = 11.7 ln y^+ −17.0 is shown as a dashed line (Virk 1975). It can be seen that profiles with the lowest F_T values have the largest departure from the logarithmic law of the wall. As F_T increases, profiles of $\langle U \rangle^+$ begin to approach the logarithmic law of the wall for Newtonian flows. For flows with an F_T = 1, the difference between the measured $\langle U \rangle^+$ within the outer layer and the Newtonian log-law tends to increase as c increases from 50 to 75 ppm — compare the blue profiles in Figure 4.12(c) with Figure 4.12(d). This is consistent with previous studies that the upward shift in the outer layer of the inner scaled velocity profile is proportionate to the drag-reduction level (Virk 1971; White *et al.* 2012).

Low-concentration PAM solutions demonstrated a deviation from the expected skin friction values for Newtonian turbulent flows. This deviation, which can be attributed to the drag-reducing effect of polymers, was observed at various Re for 50 ppm and 75 ppm PAM solutions. Furthermore, low-concentration PAM solutions exhibited onset phenomena for drag reduction. This implies that the skin friction values increased with increasing Reynolds number until reaching the onset point, after which they decreased as drag reduction took effect with further increases in Reynolds number. Values of F_T also indicated a transition from laminar to turbulent flow at specific Re that was generally higher than the critical Re of the Newtonian flows. Overall, the results demonstrated that the channel flow of low-concentration PAM solutions have a delayed transition to turbulence and less skin friction at higher Re

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than Newtonian channel flows. Moreover, velocity profiles show that low-concentration PAM solutions exhibit asymmetry in transitional flow conditions, with profiles becoming blunter as F_T values increase, similar to Newtonian cases. Inner-scaled velocity profiles for low-concentration solutions reveal that profiles with lower F_T values deviate more from the logarithmic law of the wall, while profiles approach the law as F_T increases. Furthermore, when concentration increases from 50 ppm to 75 ppm for flows with F_T of 1, the difference between measured $\langle U \rangle^+$ and the Newtonian log law grows, indicating an upward shift in the outer layer of the inner-scaled velocity profile proportional to the drag reduction level. The turbulent spots observed in low concertation solutions appear similar in morphology to Newtonian turbulent spots, albeit slightly more elongated streaks were present connecting to the leading edge.
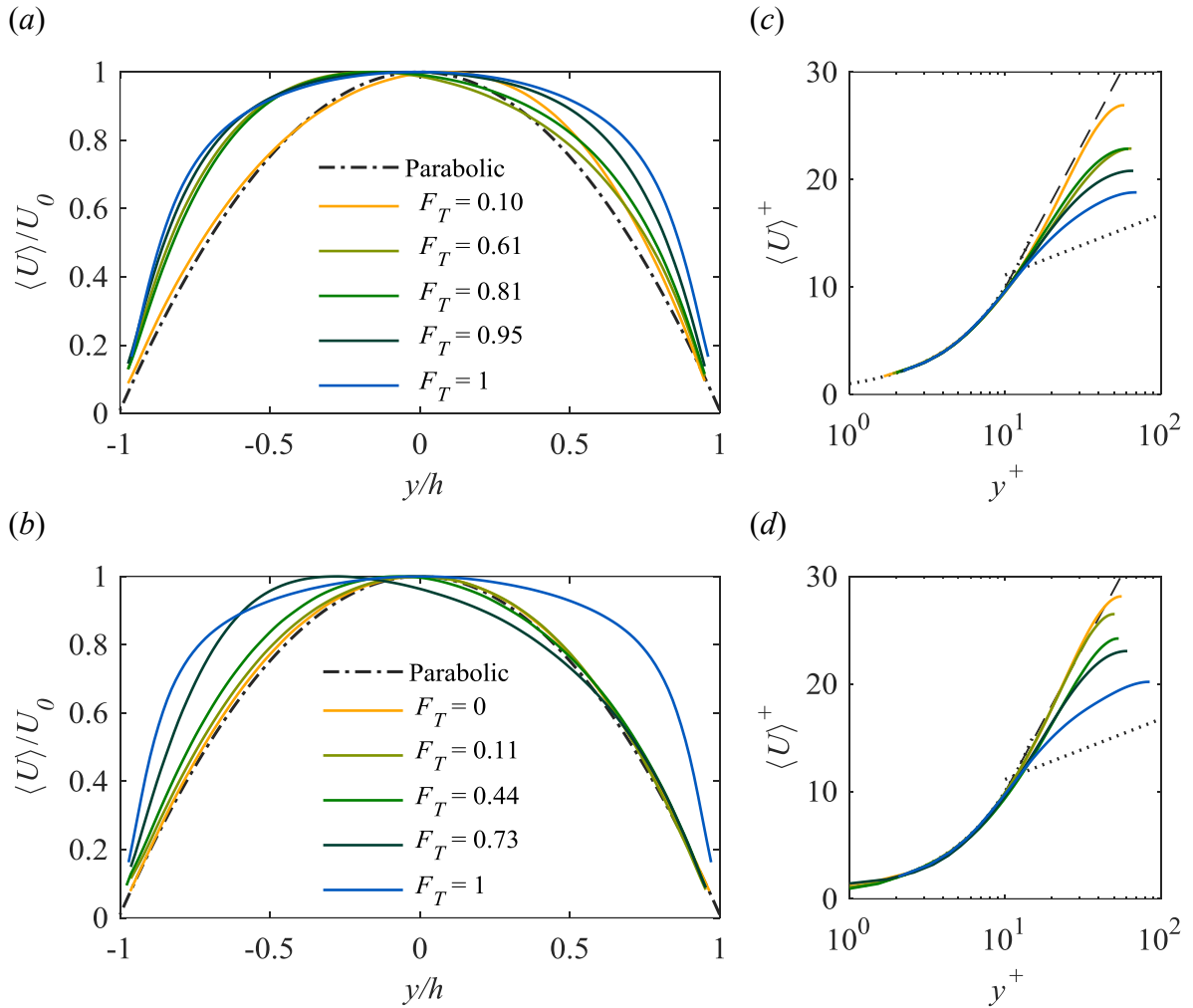
Figure 4.12 The velocity profile for laminar, transitional and turbulent cases for low-concentration solutions are plotted for (*a*) 50 ppm outer scaling, and (*c*) 50 ppm inner scaling. Reynolds numbers in order of increasing F_T: 1460, 1950, 1960, 1910, 1850 (*b*) 75 ppm outer scaling, (*d*) 75 ppm inner scaling. Reynolds numbers in order of increasing F_T: 1750, 1775, 1760, 2020, 2670. Dotted lines show the viscous sublayer and logarithmic law of the wall; Virk's (1970) velocity profile is shown with a dashed line.

4.3 Transition for high-concentration PAM solutions

Larger concentration PAM solutions, with c of 100 and 150 ppm, demonstrated distinct behaviours compared to both Newtonian and lower concentration PAM flows. In this section, the results of the 100 and 150 ppm solution experiments are presented. Measurements of C_f for the 100 ppm PAM solution, are shown in Figure 4.13. Time-resolved data collection was used to acquire data for a valve setting with low Re. Then three valve settings with Re in the transitional range were tested using long-duration double-frame data collection. Consequently, the data for the valve setting with the highest Re was collected using the time-resolved high-speed system. The first cluster of C_f measurements at nominal Re values of 1530 overlap with the expected C_f values for laminar flow. The next measurements at $Re = 2280$ start to deviate from the laminar trend. Measurements of C_f at nominal Re of 3310 continue to depart from the laminar trend with repeated data points showing a wide range of values between the laminar and MDR trends in C_f versus Re. At nominal Re of 4570, the scatter of repeated measurements gets smaller. Measurements of C_f for nominal $Re = 5350$ overlap with each other and lie on the MDR asymptote.
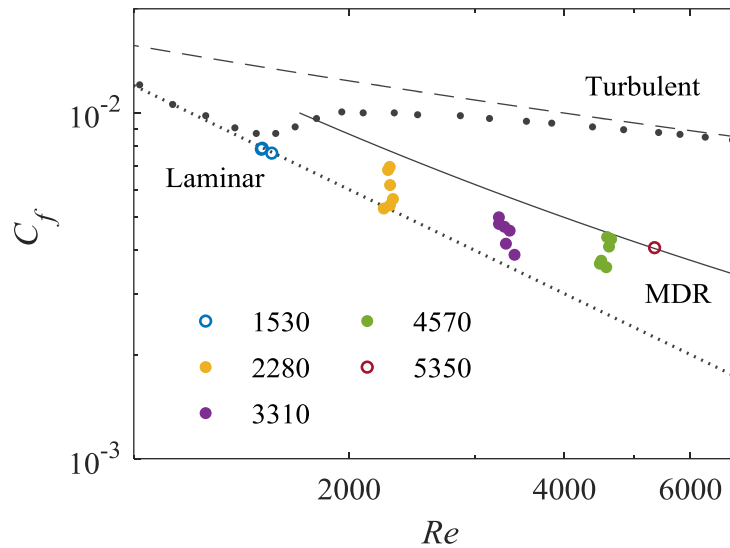
Figure 4.13 Skin friction factor (C_f) plotted as a function of the Reynolds number for 100 ppm solutions of PAM. Patel & Head (1969) data is shown as grey filled circles. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements.

Figure 4.14 demonstrates the measurements of C_f for the 150 ppm PAM flows as a function of *Re.* Below the nominal *Re* of 2810, all measurements of C_f follow the laminar trend closely. It is not until the nominal *Re* of 3670 that values of C_f begin to deviate from the laminar trend. The deviation between measurements of C_f for the 150 ppm PAM flow and the laminar C_f versus *Re* trend increases as *Re* grows from 3670 to 4640. Eventually, at the nominal *Re* of 5370, measurements of C_f reach the MDR asymptote. Overall, we observed that the skin friction factor values for high-concentration PAM solutions exhibit type B drag reduction characteristics. This is evidenced by the absence of an increase in the skin friction coefficient with increasing Reynolds number prior to the onset of drag reduction, indicating that no onset

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phenomena were detected. Furthermore, the flow does not transition to Newtonian turbulence. Instead, by increasing *Re*, the skin friction factor departs from laminar values, entering a state of drag-reduced turbulence. As the Reynolds number increases further, C_f data approaches the MDR values from below.
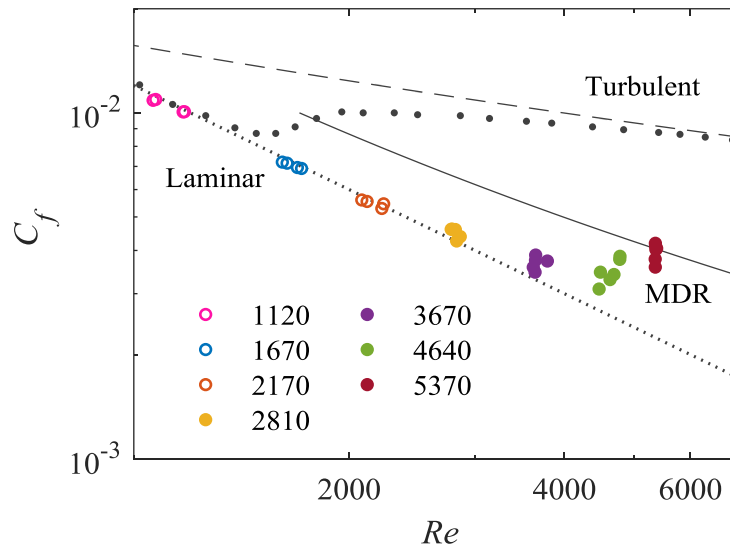
Figure 4.14 Skin friction factor (C_f) plotted as a function of the Reynolds number for 150 ppm solutions of PAM. Patel & Head (1969) data is shown as grey filled circles. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements.

Figure 12(*c*) shows measurements of F_T versus *Re* for the 100 ppm PAM flows. Below the nominal *Re* of 2280, all flows are laminar with an F_T value of 0. For the nominal *Re* of 2280, the flows reflect laminar/turbulent intermittency with six repeated measurements having F_T values spanning from 0.10 to 0.85. At the nominal *Re* of 3310, the flows remain highly intermittent, with values of F_T between 0.26 to

0.92. Increasing nominal Re to 4570, the 100ppm PAM flows reflect less intermittency with F_T between 0.60 and 1.0, and a bias towards being more turbulent. Overall, the 100 ppm PAM solutions exhibit transitional flow patterns from Re of 2280 to 4570. Compared to Newtonian and low-concentration PAM solutions, the 100 ppm PAM solution transitions to turbulence at a much larger Re and demonstrates intermittency over a wider Re range.
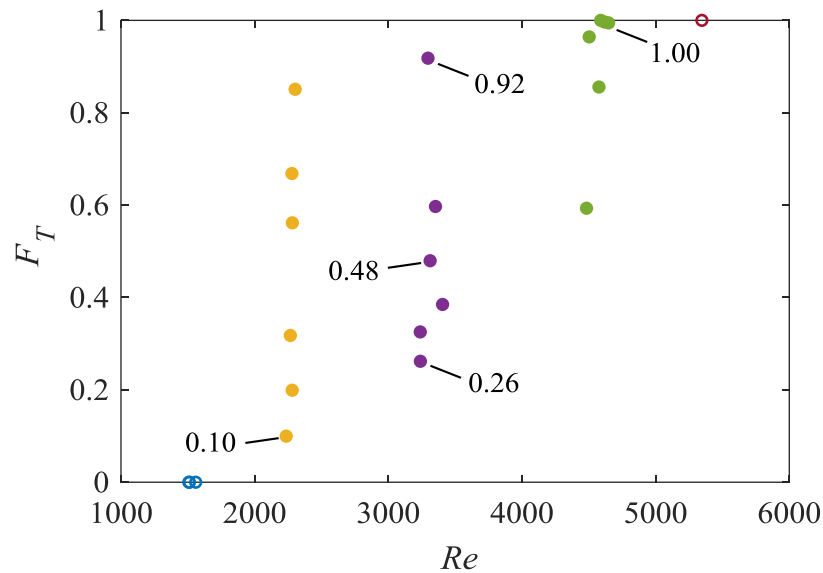
Figure 4.15 The turbulent fraction (F_T) for 100 ppm solutions of PAM is shown versus the Reynolds number. Colours show nominal Re same as Figure 4.13. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements. The velocity profiles for data points with annotated F_T will be illustrated.

Values of F_T versus Re are shown in Figure 4.16 for the 150 ppm PAM flows. Below the nominal Re of 2810, all flows have F_T of zero and are laminar. At the

nominal Re of 3670 the flow field becomes intermittent with six repeated measurements having F_T values ranging from 0.15 to 0.67. Increasing the Re to 4640, values of F_T still show significant laminar-turbulent intermittency with values of F_T that range from 0.11 to 0.86. Finally, at the highest Re of 5370 the flow field becomes fully chaotic and the F_T is 1.0. Results of the 100 ppm and 150 ppm PAM flows demonstrate that the critical Re is larger for high-concentration PAM solutions compared to Newtonian fluids and low-concentration PAM solutions. Also, the range of Re that exhibit intermittency extends as the PAM concentration is increased. The transitional Re band (the difference between highest Re with $F_T = 0$ and lowest Re with $F_T = 1$) for 100 ppm solution is observed to be 2465 and for 150 ppm is 2500.
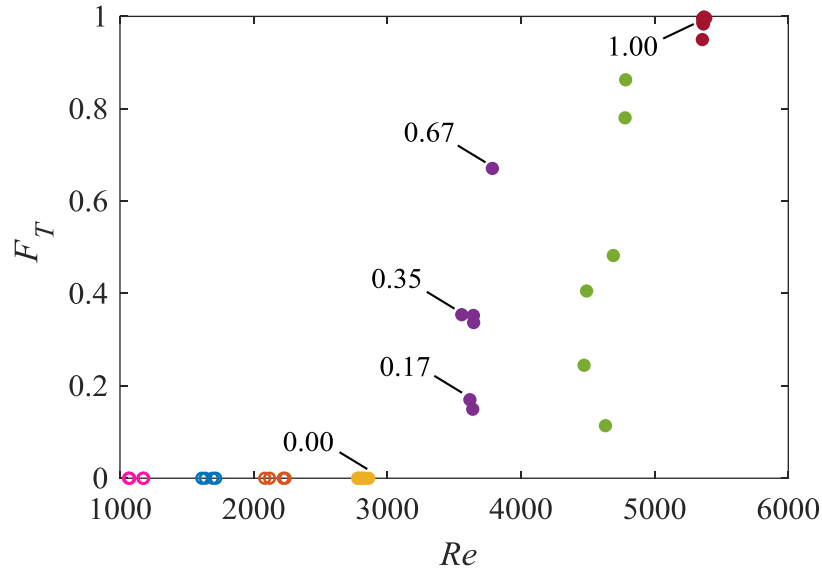
Figure 4.16 The turbulent fraction (F_T) for 150 ppm solutions of PAM is shown versus the Reynolds number. Colours show nominal Re same as Figure 4.14. Filled symbols represent long-duration data measurements and hollow symbols show time-resolved measurements. The velocity profiles for data points with annotated F_T will be illustrated.

Figure 4.17 shows $U/\langle U_c \rangle$ with respect to t' along the streamwise-wall-normal plane for the high-concentration PAM flows. Figure 4.17(*a*) demonstrates $U/\langle U_c \rangle$ for the laminar flow of PAM with $c = 150$ ppm and $Re = 2800$. The flow is visually steady with no apparent chaos. By employing equation (3), the turbulence intensity TI along $y = 0$ in the flow depicted in Figure 4.17(*a*) is calculated to be 2.5%. This value is comparable to the measurements of TI for channel flow just prior to transition conducted by Durst *et al.* (1998). Figure 4.17(*b*) shows $U/\langle U_c \rangle$ for PAM with $c = 150$ ppm, $Re = 3650$ and $F_T = 0.27$. Instabilities can be seen in the flow close to the wall

region. These instabilities did not successfully reach the channel centerline, except during the instance when t' was between 200 and 250. Shekar *et al.* (2020, 2021) conducted direct numerical simulations of 2D channel flow and observed the relationship between the Tollmien-Schlichting (TS) attractor and elasto-inertial turbulence (EIT) in a dilute polymer solution. They found that the transition between the two states is directly tied to the strength of the TS critical layer fluctuations and can be attributed to a coil-stretch transition. These near-wall TS-like instabilities are not observed in pipe or plane Couette flow and have just been observed in 2D channel flow. The near-wall instabilities observed in figure Figure 4.17(*b*) might be attributed to these TS-like instability sheets.

In Figure 4.17(*c*) with $F_T = 0.54$ and $Re = 3800$, the near wall instabilities penetrate to the channel centerline at several t' values of approximately 40, 180, 250 and 280. Figure 4.17(*d*) demonstrates the contours of $U/\langle U_c \rangle$ for the 150 ppm PAM flow with $Re = 4800$ and an F_T of 0.74. Multiple chaotic turbulent patches are visible between t' of 40-100, 150-175, 200-375 and 450-485. Lastly, Figure 4.17(*e*) shows the 150 ppm PAM flow with a Re of 5360 and a F_T of 1. The flow is visually chaotic along all values of y and t'. Figure 4.17 demonstrates the transition process in high-concentration PAM.
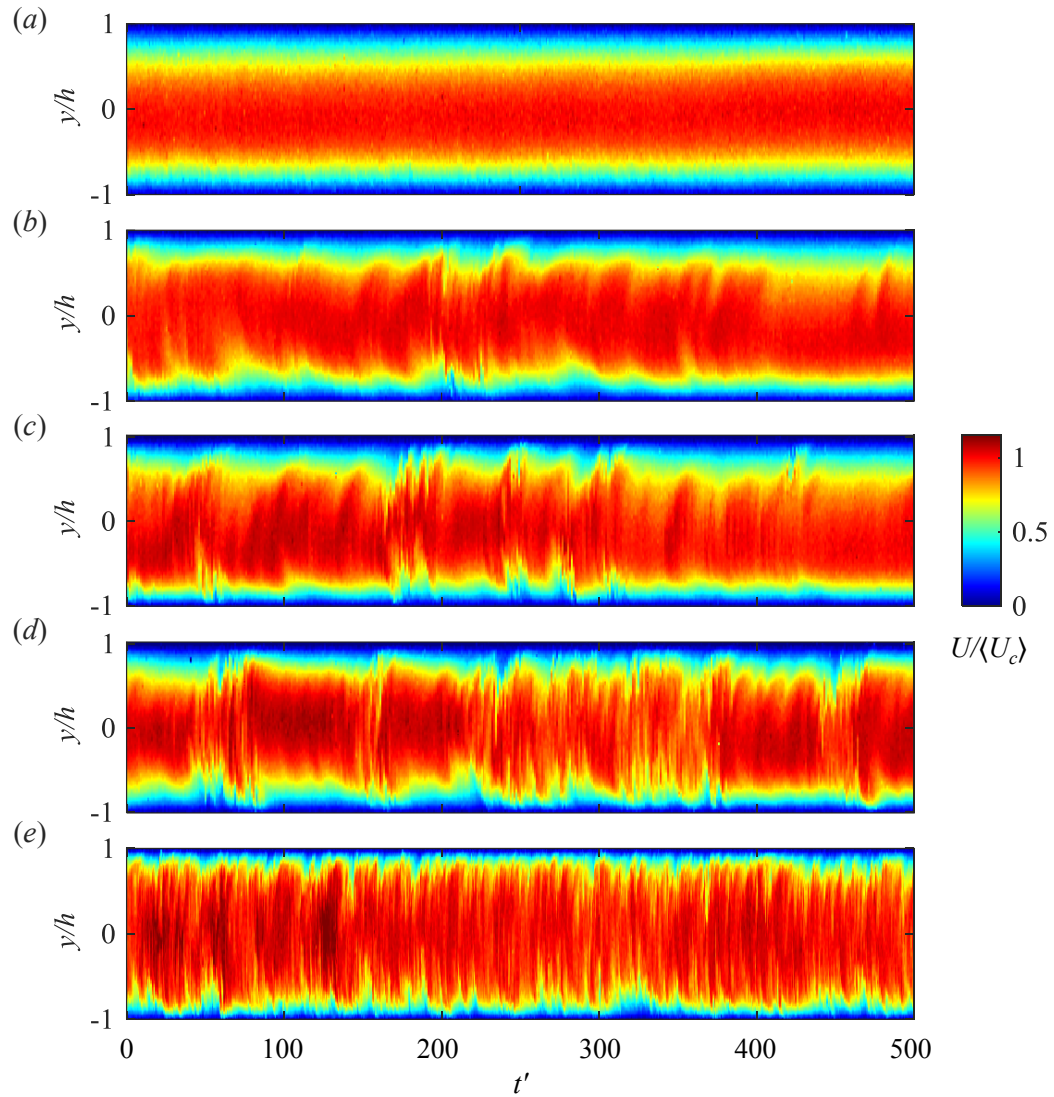
Figure 4.17 Spatial contours of normalized streamwise velocity ($U/\langle U_c \rangle$) from streamwise wall-normal measurements showing various flow states for 150 ppm PAM solution. (*a*) Laminar $F_T = 0$, $Re = 2800$, (*b*) transitional $F_T = 0.27$, $Re = 3650$, (*c*) transitional $F_T = 0.54$, $Re = 3800$, (*d*) transitional $F_T = 0.74$, $Re = 4800$ (*e*) turbulent $F_T = 1$, $Re = 5360$.

Figure 4.18 shows the measurements of $U/\langle U_c \rangle$ along the streamwise-spanwise plan with respect to t' for the high-concentration PAM solution with $c = 150$ ppm. Figure 4.18(*a*) corresponds to the lowest valve setting with a nominal Re of 2810 and demonstrates a laminar flow with very small fluctuations. Figure 4.18(*b*) to (*d*) displays $U/\langle U_c \rangle$ for a transitional flow of the high-concentration PAM solution at nominal $Re \approx 3670$. Figure 4.18(*b*) illustrates a long low-speed streak at z/h of approximately 1. However, in contrast to Newtonian and low-concentration flows, the low-speed streak is not attached to any turbulent spot. Figure 4.18(*c*) depicts two low-speed streaks at approximate z/h of 0 and 2. It could be clearly seen that these streaks are not attached to any turbulent spots. Figure 4.18(*d*) shows a long low-speed streak at z/h of approximately 0 and extended along the entire domain of t'. At the transitional Re, no recognizable turbulent spots are observed, unlike the water and lower concentration PAM flows. Instead, only low-speed streaks, confined to a limited spanwise distance, can be seen in the transitional regime. Previously, Xi & Graham (2012) noted in their numerical simulations of channel flow that the transitional state existing between laminar and turbulent flow exhibited minimal three-dimensional qualities. This lack of three-dimensionality was also evident in the lower-branch exact coherent states near the laminar-turbulent boundary identified by Wang *et al.* (2007). However, prior to our study, no experimental flow visualizations had captured these streamwise transitional streaks.

Figure 4.18(*e*) illustrates the chaotic state of the flow for the high-concentration PAM solution at Re of 4640. The chaos and mixing in the z-axis direction are observed

to be less dominant compared to water and low-concentration solutions, seen in Figure 4.4 and Figure 4.11. The flow fields illustrated in Figure 4.18(*b*) and (*c*) have smaller velocity fluctuations in the streamwise-spanwise plane relative to Newtonian and low-concentration PAM conditions. Turbulent spots, which were present in the water and low-concentration cases, were absent in the high-concentration experiments in a similar form.
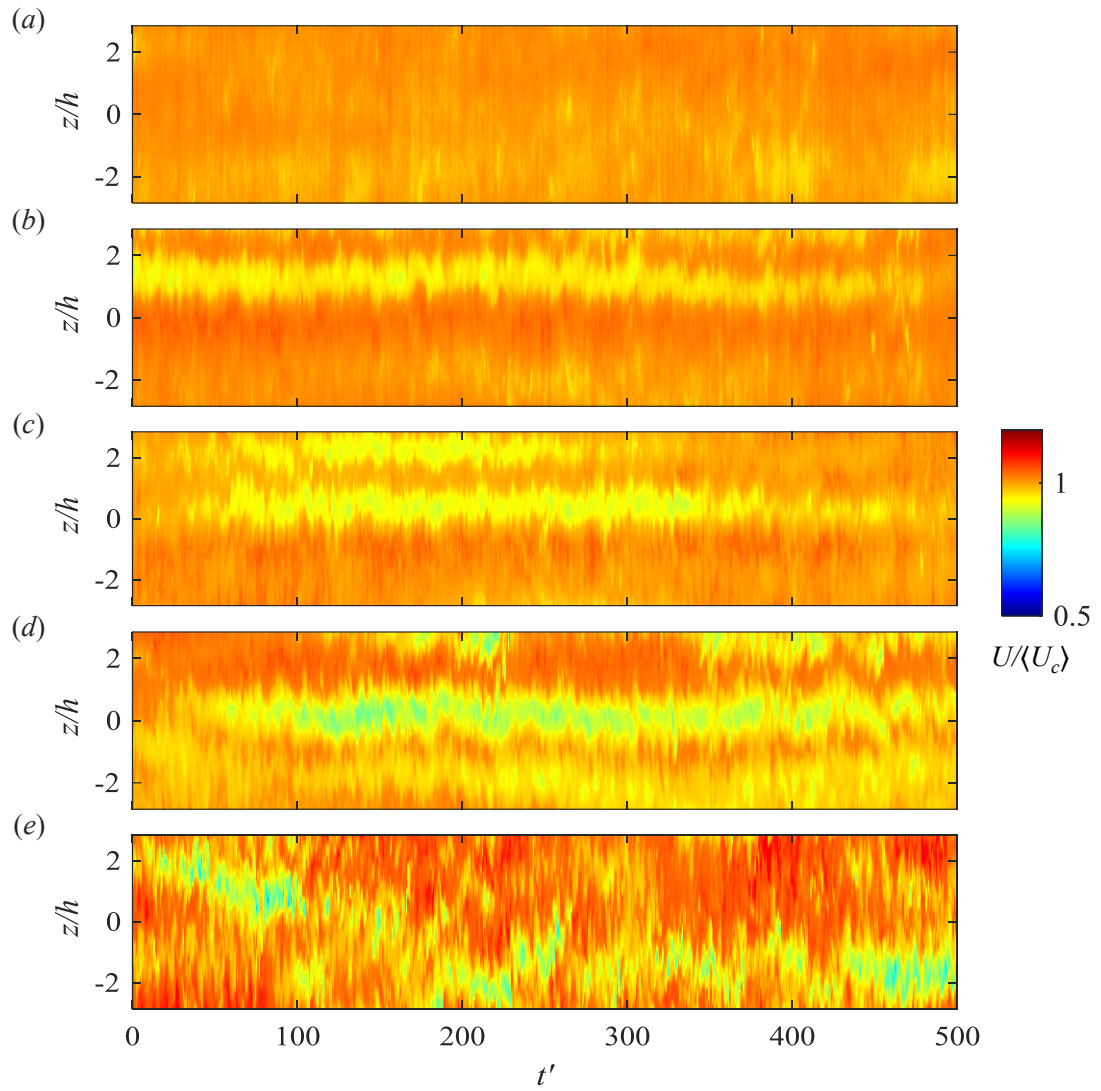
Figure 4.18 Spatial contours of normalized streamwise velocity ($U/\langle U_c \rangle$) from streamwise spanwise measurements showing (*a*) laminar $Re \approx 2810$, (*b*) to (*d*) three transitional cases $Re \approx 3670$ and (*e*) turbulent $Re \approx 4640$ flow fields in 150 ppm solution.

Figure 4.19 shows the velocity profiles acquired for the high-concentration solutions in outer- and inner-scaling. Comparing Figure 4.19(a), (c) to Figure 4.5(a) reveals that the laminar velocity profile deviated from the expected parabolic trend. The deviation is present in low-concentration solutions as well, however, it increases by increasing c. This deviation can be attributed to shear-thinning behaviour in the fluid, causing reduced viscous forces near the channel wall, and as a result a flattened velocity profile (Bird et $al.$ 2006). Furthermore, the asymmetry in transitional velocity profiles are also observed in the data for high-concentration fluids, as it is shown in figures 15(a) and (b).

When examining the deviation from the Newtonian logarithmic law of the wall, it was found that the largest deviation occurred in the high-concentration cases, as seen in Figure 4.5(c) and (d). One can notice that for F_T less than 0.5 in high-concentration solutions, an occasional surpassing of Virk's (1970) velocity profile is observed. This surpassing was previously observed in several investigations (Dubief et $al.$ 2005; Escudier et $al.$ 2009; Li et $al.$ 2006; Ptasinski et $al.$ 2001). Possible justifications include shear-thinning and polymer aggregation in experimental studies, as well as the use of different artificial stress diffusion schemes in computational studies. Additionally, the validity of Virk's (1970) velocity profile may be incomplete. However, almost all observations fall within the 95% confidence range of the original linear fit of the polymer data to a Prandtl-von Kármán law (Graham 2014). Moreover, Xi & Graham (2012) and Pereira et $al.$ (2019) observed surpassing of Virk's (1970)

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velocity profile during instances of marginalized weak turbulence in their flow fields, which could explain the surpassing observed in Figure 4.5(c) and (d).

Comparing Figure 4.5(c) and (d), the deviation from the log-law is higher in the 150 ppm concentration than in the 100 ppm case. Even though the deviation from the log law does decrease with an increase in F_T, even in the flow's fully chaotic state, the inner-scaled velocity profile is significantly different compared to the logarithmic law of the wall. Previously Virk (1971) suggested that the behaviour of the mean velocity distribution depends on the achieved drag reduction and is dynamically different from the Newtonian flow.
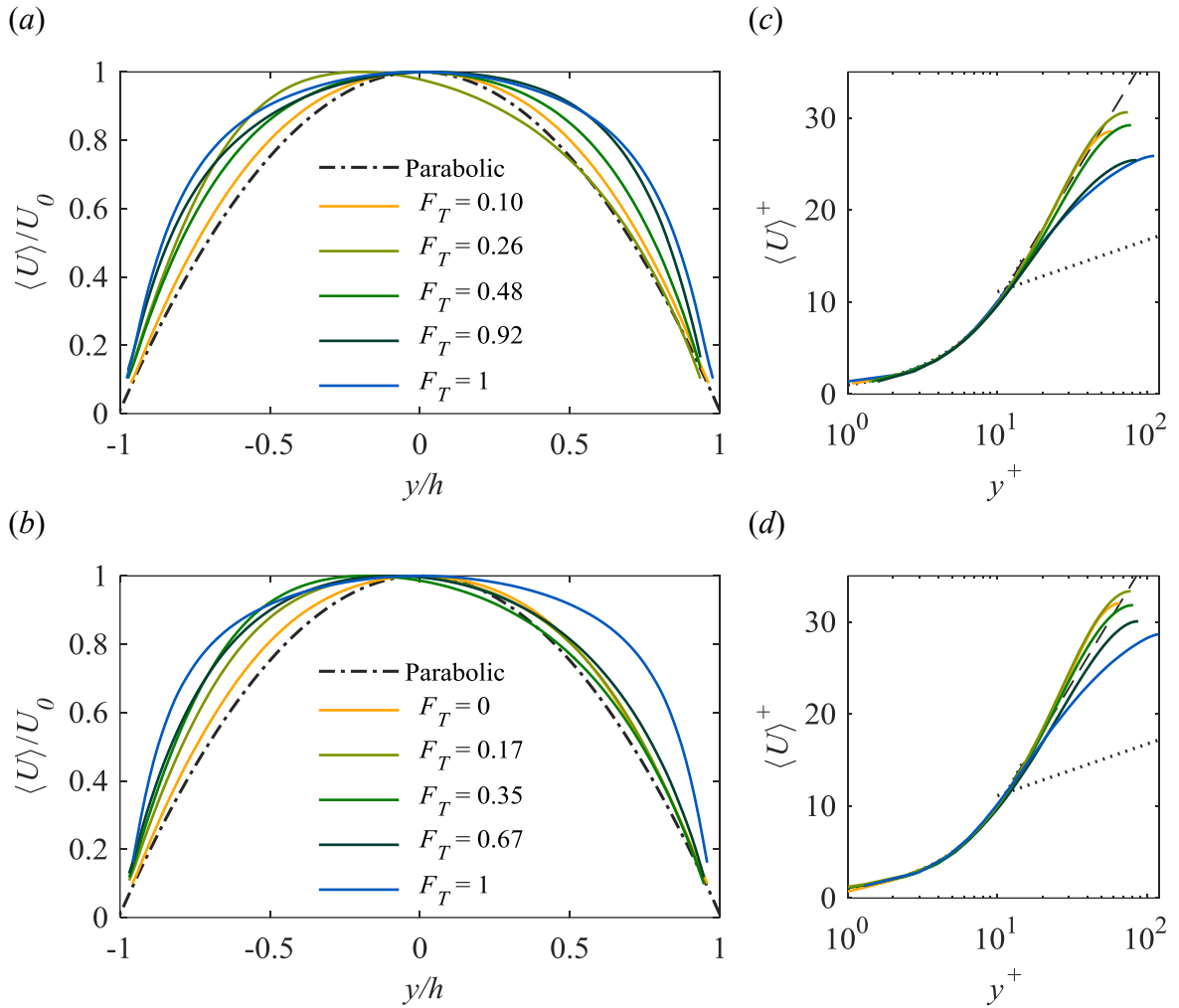
Figure 4.19 The velocity profiles for laminar, transitional and turbulent cases for high-concentration PAM solution. (*a*) 100 ppm outer scaling, (*b*) 100 ppm inner scaling. Reynolds numbers in order of increasing F_T: 2240, 3240, 3315, 3300, 4590. (*c*) 150 ppm outer scaling and (*d*) 150 ppm inner scaling. Reynolds numbers in order of increasing F_T: 2860, 3620, 3560, 3790, 5360. Dotted lines show the viscous sublayer and logarithmic law of the wall; Virk's (1970) velocity profile is shown in a dashed line.

5. Discussion

This study investigated the effect of polymers on laminar-turbulent transition in channel flows. The C_f for low-concentration solutions of PAM with c of 50 ppm and 75 ppm, increased with growing Re until the onset of drag reduction. After which, C_f begins to reduce with increasing Re. At higher Re, values of C_f are reduced to values close to the MDR asymptote. Since drag reduction shows an onset point, the low-concentration experiments showed a type A drag reduction behaviour. The C_f data obtained from high-concentration solutions (100 ppm and 150 ppm) exhibit a laminar trend up to a higher Reynolds number, after which they deviate and approach the MDR asymptote, indicative of type B drag reduction. Previous research by Mohsenipour *et al.* (2013) reported a similar shift in the drag reduction behaviour with an increase in concentration in their pipe experiments.

Comparing the measurements of the turbulent fraction F_T for water and the PAM flows showed that the transition to turbulence was delayed to larger Re in the polymeric flows, with the delay increasing as the polymer concentration increased.

These results are in line with previous literature that has shown that flexible polymers can suppress Newtonian turbulence and delay the laminar-turbulent transition. Early work by Giles & Pettit (1967) observed that increasing polymer concentration monotonically increased the critical Reynolds number required for transition. Compared to a value of 2240 for pure water, their highest polymer concentration solution delayed transition until a Reynolds number of 26,000. Further research quantified the underlying mechanisms for this transition delay. Pinho & Whitelaw (1990) attributed the effect to shear-thinning and suppression of turbulent fluctuations in normal stress components. Draad *et al.* (1998) found polymers stabilize the flow with respect to forced disturbances, increasing the critical disturbance velocity compared to water. However, they noted this delay occurred only for fresh, extended polymer chains. While not evident from friction factor plots, Escudier *et al.* (1998) used axial velocity fluctuation intensity to clearly identify delayed transition with increasing polymer elasticity and extensional viscosity. Finally, Samantha *et al.* (2013) systematically increased polymer concentration, finding puff survival rates shifted to progressively higher Reynolds numbers. The concentration dependence indicated polymers postpone turbulence onset in faster than a linear trend, quantifying the transition delay effect. However, it should be noted that all of the mentioned investigations were carried out in pipe flows. Hence, given our observation of transition delay, one can conclude that the underlying turbulence-suppressing mechanisms are present in channel flows as well.

In addition, the transition band – the range in *Re* where flows exhibited regions of laminar-turbulent intermittency and an F_T between 0 and 1 – also became wider as the polymer concentration increased. For high-concentration PAM flows within the transitional range of *Re*, the flows exhibit stronger instabilities in the zones between the turbulent spots, as observed in velocity measurements along the streamwise-wall-normal plane. This behaviour is in contrast to the behaviour of water and lower concentration PAM flows, where pronounced turbulent spots are observed with calm laminar regions in between them. Furthermore, the time variation of the centreline velocity observed in the streamwise-wall-normal plane were more gradual, consistent with the findings of Samanta *et al.* (2013), who reported that turbulent puffs could not be detected for polymer concentrations greater than 200 ppm. They reported that a different form of disordered motion sets in at a lower *Re.* However, it should be noted that Samanta *et al.* (2013) conducted their experiments in a pipe flow facility, and according to the comprehensive review by Castillo Sánchez *et al.* (2022), the instabilities and pathway to turbulence and MDR could differ in channel and pipe flows. In the streamwise-spanwise measurements of high-concentration solutions, long low-speed streamwise streaks are observed within the transitional Reynolds number range. Since no turbulent spots were observed in the streamwise-spanwise measurements of high-concentration solutions, these low-speed streaks may be alternative intermittent flow structures on the path from laminar to turbulent flow. Moreover, Lemoult *et al*. (2014) illustrated that the turbulent spots of channel flow evolve from a streaky structure. Connecting our observations with theirs suggests that

high polymer concentrations may interfere more noticeably with the process of turbulent spot growth in the spanwise direction.

Figure 5.1 displays the turbulence intensity TI percentage calculated along the centerline of the channel for all experiments. For intermittent cases where $0.2 \leq F_T \leq 0.8$, TI is calculated separately for the laminar and turbulent sections that are established using the detection method from section 2.2. The TI of the laminar portions is represented using hollow symbols, while the TI of the turbulent portion of the signal is shown using filled symbols in Figure 5.1. It is noteworthy that as Re increases in high-concentration cases, the two branches of laminar and turbulent intensity appear to converge. The reduction in the higher TI branch as Re increases can be attributed to two factors: First, an increase in the average centerline velocity due to an increase in flow rate. To assess the effect and importance of this factor, one can compare polymeric cases to higher Re Newtonian cases, as shown in Figure 5.1 with gray markers (both circles and starts). Although Newtonian flows exhibit a reduction in the higher branch of TI, the drop in TI values is more pronounced in polymeric solutions. The second reason for the decrease in the higher TI branch as a function of Re for polymeric cases is the reduced centerline velocity fluctuations associated with increasing solution concentration as observed in spatio-temporal contours. For the upper TI branch and at a constant Re range of 3000 to 3500, the TI values for 100 ppm solutions are generally lower than those for 75 ppm solutions. A similar trend is observed in the Re range of 4500 to 5000 for 100 ppm and 150 ppm cases.

In addition to the decrease in the upper branch of TI, an increase is also observed in the lower branch in Figure 5.1. The TI values increase from 0.75% for the water cases at *Re* = 1500 to 1.17% for the 100 ppm cases at *Re* = 3650 and 1.77% for the 150 ppm experiments at *Re* = 5365. This trend could represent the centerline instability underlying the high-concentration polymer cases. This instability is present in the laminar flow regions between turbulent spots, similar to the observation in Figure 4.17, which would result in larger centerline velocity fluctuations and consequently higher TI for these regions.
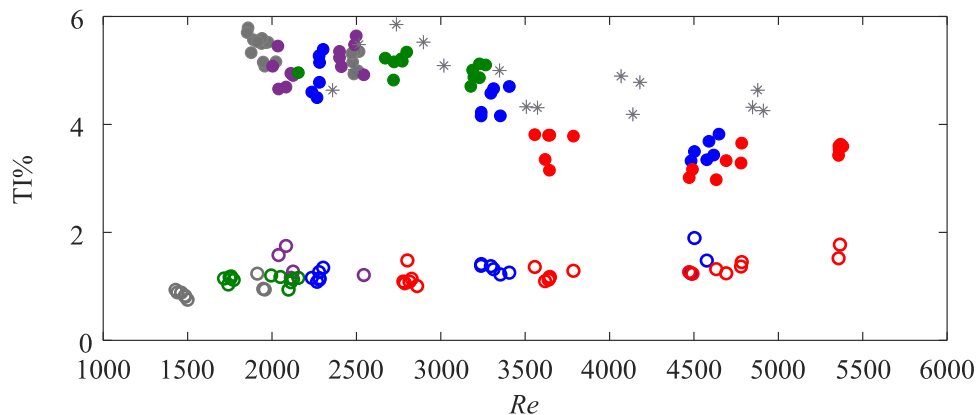
Figure 5.1 Turbulence intensity (TI) calculated along the centerline of the channel. Hollow symbols represent laminar segments of flow and solid-filled symbols show turbulent parts. The symbol colours are similar to Figure 3.4 representing the polymer concentration. Gray markers represent water data, star symbols show time-resolved PIV measurements.

Figure 5.2 presents data for all five solutions in Weissenberg number, $Wi = \dot{\gamma}\, t_e$, and Re space. Each data point is coloured according to the fraction of turbulence, which is indicated by the colour bar in the figure. The figure is divided into four zones, namely laminar, transitional, turbulent, and MDR based on F_T and C_f values. The MDR zone comprises all data points that are within 15% of the drag reduction of the MDR line in the C_f-Re plots. It is important to note that the boundaries delineated in the figure are approximate, and there are uncertainties associated with the limited number of data points and rheology measurements. Similar but qualitative Wi-Re phase diagrams have been presented in previous studies, such as Graham (2014), Xi (2019) and Castillo Sánchez et $al.$ (2022). Also, Re versus polymer concentration maps have been shown in Choueiri et al. (2018) and Chandra et $al.$ (2020) for pipe and microtube flows, respectively. A horizontal path on the $Wi = 0$ line indicates the Newtonian laminar to turbulent transition. When polymers are introduced to the flow ($Wi > 0$), the transitional region expands, and the expansion increases with increasing Wi. The transition to the $F_T = 1$ region also occurs at a higher Reynolds number. Moreover, moving vertically with increasing Wi at a narrow range of Re reveals the reverse transition behaviour through the intermittent flow field. This is consistent with the observations made by Lopez et al. (2019) for pipe flow. Additionally, type B drag reduction behaviour and previous observations (Choueiri et $al.$ 2018; Lopez et $al.$ 2019; Samanta et $al.$ 2013) suggests that for sufficiently high Wi, a fluid can transition directly from a laminar state to the MDR state with little to no intermittency forming the laminar-MDR zones boundary.

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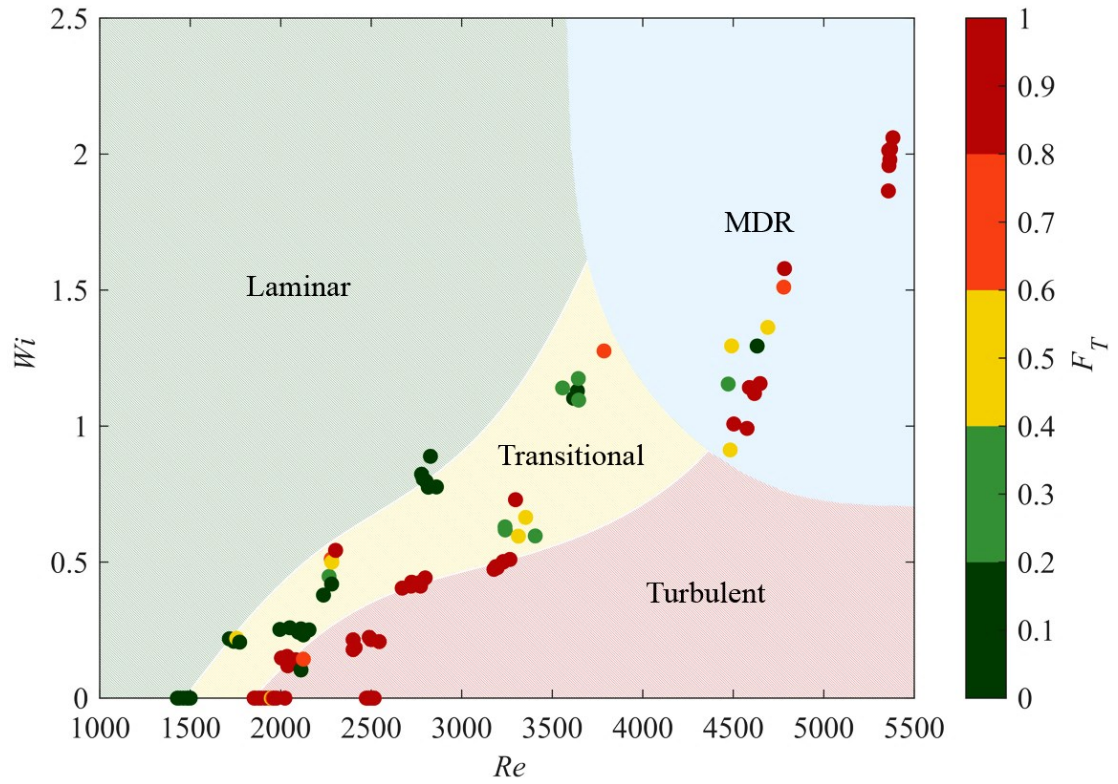
Figure 5.2 Data for all five solutions in Weissenberg number and Reynolds number space, coloured by the fraction of turbulence as shown by the colour bar. Indicated "Laminar", "Transitional", "Turbulent", and MDR zones have approximate boundaries.

6. Conclusions

In this study, the flow characteristics of water, low (50 and 75 ppm) and high-concentration (100 and 150 ppm) solutions of polyacrylamide (PAM) in a rectangular channel flow facility were systematically investigated utilizing particle image velocimetry in streamwise-wall-normal and streamwise-spanwise planes. The skin friction coefficient (C_f) and the fraction of turbulence (F_T) were measured across a range of Reynolds numbers through extensive experimental campaigns. For transitional flows, measurements were repeated at least six times at each flow rate to ensure sufficient repeatability and reliability in quantifying the intermittent laminar-turbulent transitions. Velocity field measurements were conducted to characterize the Newtonian and polymeric flows in laminar, transitional, and fully turbulent regimes. This experimentalstudy provides new insights into how dilute polymer additives influence the laminar-turbulent transition.

This experimental study provides new insights into how polymer additives influence the laminar-turbulent transition in rectangular channel flows. For the

baseline Newtonian fluid, the evolution of turbulence statistics and critical Reynolds number range of 1900-2200 aligned closely with previous literature, validating the experimental methods.

With the introduction of lower polymer concentrations, the transitional regime expanded substantially, with intermittency occurring from $Re = 2000$-3000 compared to 1900-2200 in the Newtonian case. The onset of sustained turbulence was delayed to $Re \geq 3000$, compared to 2200 for the Newtonian fluid. The solutions exhibited a drag reduction onset point, following a type A pattern with rising skin friction during the laminar-turbulent transition, then clearly dropping friction above a threshold Reynolds number. Transitional flows displayed recognizable turbulent spots and asymmetric mean velocity profiles, analogous to Newtonian transition.

In contrast, higher polymer concentrations demonstrated significant differences. Most notably, they showed a departure from the laminar skin friction trend toward the maximum drag reduction asymptote, consistent with type B drag reduction behaviour. The polymers strongly hindered the emergence and spreading of turbulent spots during the transition. Instead, elongated streamwise streaks dominated the transitional flows at higher concentrations for Re from 3000-5000.

Polymer flows at all concentrations exhibited enhanced centerline velocity fluctuations with turbulence intensity increasing from 0.75% to 1.77% in laminar zones between turbulent events. However, velocity fluctuations decreased significantly in fully turbulent regions, dropping from 5% in Newtonian flows to 3% in high-concentration polymer solutions.

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6.1 Future Work

While this thesis provides new insights into the laminar-turbulent transition and turbulence modulation induced by dilute polymer solutions, opportunities remain to further expand the understanding of viscoelastic turbulence dynamics.

Advanced optical measurements and computational fluid dynamics simulations would enable more in-depth investigations of the polymer-modified coherent structures and instability mechanisms governing the transition from laminar to turbulent flow. For example, techniques such as tomographic particle image velocimetry could capture detailed velocity statistics and turbulence quantities within the transitional flow structures. Direct numerical simulations, if properly formulated and validated, may shed light on the polymer stretching dynamics and internal stress balances underlying the formation transitional flow structures.

Exploring the impacts of complex geometries and flow configurations beyond canonical flows merits study as well. The transitional statistics and coherence structures could differ substantially in non-rectangular ducts, flows over curved surfaces, or flows with swirl and rotation.

The range of fluid elasticity and extensibility could be expanded by testing solutions of flexible polymer species beyond polyacrylamide. Varying polymer molecular weight and chain branching may induce further alterations to the transition process and sustainment of chaotic motions. Ultimately, the goal is to develop comprehensive predictive capabilities - to quantitatively determine critical stability

parameters and define transition criteria encompassing an extensive range of viscoelastic fluid properties.

Overall, the foundations established in this thesis will motivate and inform extensive future work unraveling the intricacies of instabilities in non-Newtonian flows. This will provide deeper insights into polymer-turbulent interactions, which may reveal more about the mechanisms underlying drag reduction.

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Appendices

A MATLAB Code for Laminar/Turbulent Detection

```matlab
%% Laminar/turbulent detection algorithm
% Load velocity data
% U_signal = loaded velocity data

%% Measurement parameters
f = 60; % Acquisition frequency (Hz)

t = 1/f.*[1:length(U_signal)]; % Time vector (s)
H = 0.016; % Channel full height (m)

%% Calculated parameters
U_mean = mean(U_signal); % Mean velocity (m/s)
u = U_signal - U_mean; % Velocity fluctuations (m/s)
t_norm = t.*U_mean/H; % Normalized time (-)

%% Apply high-pass filter
f_pass_norm = 0.05; % Normalized filter frequency (-)
f_pass = f_pass_norm*U_mean/H; % Cutoff frequency (Hz)
u_filtered = highpass(u,f_pass,f); % Filtered signal

%% Moving average and standard deviation
Filter_length_norm = 10; % Normalized filter length (-)
filter_length_datapoint = round(Filter_length_normfH/U_mean); % Length in
data points (-)
x =
movstd(u_filtered,filter_length_datapoint)./movmean(U_signal,filter_length
_datapoint); % Detection parameter (-)

%% Laminar/turbulent threshold
TR = 0.03; % Laminar/turbulent threshold (-)

%% Minimum segment length
Minimum_segment_length_norm = 25; % Normalized minimum length (-)
Minimum_segment_length_datapoint =
round(Minimum_segment_length_normfH/U_mean); % Length in data points (-)

%% Identify turbulent zones
Identify_turb_segments = bwareafilt(x>TR,
[Minimum_segment_length_datapoint, inf]);

%% Extract turbulent velocity
```

```matlab
42
43    U_turb_segments = U_signal.*Identify_turb_segments;
44    U_turb_segments(U_turb_segments==0) = NaN;
45    U_turb_stitched = U_signal(Identify_turb_segments);
46
47    %% Identify laminar zones
48    Identify_lam_segments = bwareafilt(x<TR,
49    [Minimum_segment_length_datapoint, inf]);
50
51    %% Extract laminar velocity
52    U_lam_segments = U_signal.*Identify_lam_segments;
53    U_lam_segments(U_lam_segments==0) = NaN;
54    U_lam_stitched = U_signal(Identify_lam_segments);
55
56    %% Calculate turbulence intensities
57    TI_turb = std(U_turb_stitched)/mean(U_turb_stitched);
58    TI_lam = std(U_lam_stitched)/mean(U_lam_stitched);
```

B Technical Drawings of the Flow Facility

The flow facility used in this study was designed under the supervision of Dr. Sina Ghaemi, and technical drawings were prepared by Dave Tataryn. The facility was commissioned by the writer. SolidWorks 3D CAD software was utilized for designing the flow facility components. The following pages provide detailed technical drawings of the settling chamber, contraction section, acrylic test section, and diffuser.
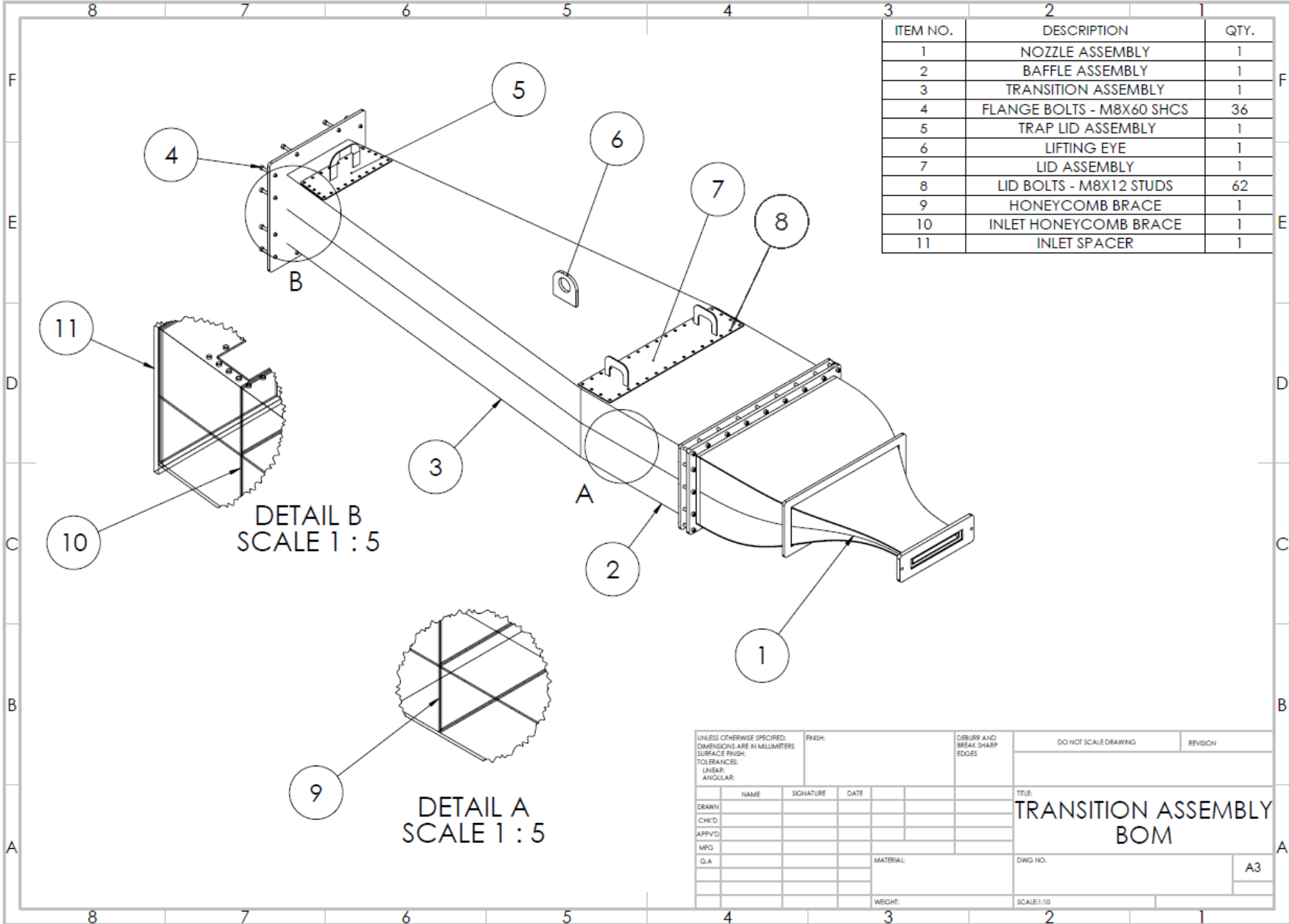
ITEM NO.	DESCRIPTION	QTY.
1	NOZZLE ASSEMBLY	1
2	BAFFLE ASSEMBLY	1
3	TRANSITION ASSEMBLY	1
4	FLANGE BOLTS - M8X60 SHCS	36
5	TRAP LID ASSEMBLY	1
6	LIFTING EYE	1
7	LID ASSEMBLY	1
8	LID BOLTS - M8X12 STUDS	62
9	HONEYCOMB BRACE	1
10	INLET HONEYCOMB BRACE	1
11	INLET SPACER	1

DETAIL B
SCALE 1 : 5

DETAIL A
SCALE 1 : 5

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

TRANSITION ASSEMBLY
BOM

MATERIAL:

DWG NO.

A3

WEIGHT:

SCALE:1:10

121

[1.18]
30.00

[44.49]
1130.00

[1.18]
30.00

[78.74]
2000.00

[3.94]
100.00

[10"]
254.00

[7.87]
200.00

122

[3.94]
100.00

⌀8.0 THRU HOLE
TYP

[9.54]
242.31

83.44°

[21.65]
550.00

[10"]
254.00

[3.15]
80.00

[4.76]
121.00

[19.69]
500.00

[59.06]
1500.00

[78.75]
2000.35

[0.31]
R8.00
TYP

[23.62]
600.00

[10.00]
254.09

123

[3.94]
100.00

6.60°

[3.15]
80.00

[33.67]
855.24

[19.96]
506.98

[19.69]
500.00

[4.76]
121.00

[79.31]
2014.58

124

WELD ALL AROUND
M8 STUDS
OTHER SIDE ONLY
ENSURE PERPENDICULARITY
TYP

WELD ALL AROUND
M8 STUDS
OTHER SIDE ONLY
ENSURE PERPENDICULARITY
TYP

E

DETAIL E
SCALE 1 : 2

	NAME	SIGNATURE	DATE		TITLE:		
DRAWN							
CHK'D					TRANISTION_TOP		
APPV'D					STUD WELD		
MFG							
Q.A			MATERIAL:		DWG NO.		A3
			11GA SS				
			WEIGHT:		SCALE:1:10	SHEET 4 OF 22	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
  LINEAR:
  ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

125

[5"]
127.00

[10"]
254.00

[23.62]
600.00

[59.06]
1500.00

[19.69]
500.00

126

[79.33]
2014.95

6.60°

R8
TYP

[10"]
254.00

[23.62]
600.00

[34.17]
867.88

[59.06]
1500.00

[19.69]
500.00

127

ITEM NO.	DESCRIPTION	QTY.
1	WELD PLATE	1
2	LID	1

2

1

128

[3.94]
100.00
C̵ TYP

([21.57])
548.00

([23.23])
590.00

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					**LID ASSEMBLY**
APPV'D					
MFG					
Q.A			MATERIAL:		DWG NO.

WEIGHT: SCALE:1:10

A3

129

[0.39]
10.00

[1.60]
40.71 TYP

[0.33]
Ø 8.50
THRU HOLE
TYP

[0.39]
10.00
TYP

[1.57]
40.00 TYP

[5.51]
140.00

[23.23]
590.00

[0.12]
3.04

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					LID
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO.	A3
			11 GA SS		
			WEIGHT:	SCALE 1:10	

130

[21.57]
548.00

[0.39]
⌀10.00
THRU HOLE
TYP

[0.39]
10.00
TYP

[0.39]
10.00 TYP

[3.86]
98.00

[4.62]
117.34
TYP

[2.31]
58.67
TYP

131

[0.38]
9.53

[0.59]
15.00

[2.48]
63.10

[0.39]
⌀ 10.00
TYP

[2.39]
60.60
TYP

[0.59]
15.00

[23.87]
606.20

[26.23]
666.20

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					EXIT FLANGE
APPV'D					
MFG					
Q.A					

MATERIAL:
3/8" SS

DWG NO.

A3

WEIGHT:

SCALE 1:10

132

[0.38]
9.53

[4.65]
118.00
TYP

[4.65]
118.00
TYP

[2.03]
51.60

[0.47]
⌀ 12.00
THUR HOLE
TYP

[0.75]
19.10

[3.35]
85.00
TYP

[0.75]
19.10

[3.35]
85.00
TYP

[0.39]
R10.00
TYP

[10.55]
268.00

[0.89]
22.50
TYP

[16.54]
420.00

133

[23.62]
600.00

[0.12]
3.04

[11.81]
300.00 ℄

[0.20]
R5.00
TYP

R2.00
TYP

[10"]
254.00

[5.02]
127.50 ℄

[0.12]
3.04
TYP

134

ITEM NO.	DESCRIPTION	QTY.
1	TRAP LID CENTERING PLATE	1
2	TRAP LID	1

2

1

	NAME	SIGNATURE	DATE		TITLE:	
DRAWN						
CHK'D					**TRAP LID**	
APPV'D					**BOM**	
MFG						
Q.A			MATERIAL:		DWG NO.	A3
			WEIGHT:		SCALE:1:10	

135

[0.12] 3.04

[0.33] Ø 8.50
THRU HOLE
TYP

[10.52] 267.28

[0.39] 10.00

[4.25] 108.00

[0.96] 24.50 TYP

[4.65] (118.00)

[0.39] 10.00 TYP

[1.23] 31.21 TYP

[11.50] 292.12

[0.20] R5.00 TYP

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					**TRAP LID**
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO.	A3
			11 GA SS		
			WEIGHT:	SCALE:1:10	

136

[0.12]
3.04

[0.39]
Ø 10.00
THRU HOLE
TYP

[9.47]
240.53

[2.10]
53.45 TYP

[0.53]
13.37
TYP

[3.07]
78.00

[0.59]
15.00 TYP

[2.88]
73.10
TYP

[10.18]
258.47

	NAME	SIGNATURE	DATE		TITLE:		
DRAWN							
CHK'D					**TRAP WELD PLATE**		
APPV'D							
MFG							
Q.A			MATERIAL:		DWG NO.		A3
			11 GA SS				
			WEIGHT:		SCALE 1:10		

137

WELD ON ℄
ALL AROUND
BOTH LEGS

PLUG WELD
ALL HOLES

138

[11.85]
301.08

[0.12]
3.04

[0.16]
R4.00
TYP

[10"]
254.00

[0.20]
R5.00
TYP

[5.75]
145.99
TYP

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					INLET BRACE
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO.	
			11GA SS		A3
			WEIGHT:	SCALE:1:10	

139

[0.38]
9.53

[10.28]
261.20

[11"]
279.40

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

INLET SPACER

MATERIAL:
3/8" SS

DWG NO.

A3

WEIGHT:

SCALE:1:10

140

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	ENTRANCE FLANGE	1/2" 304 SS	1
2	TRANSITION_SIDE	11 GAUGE 304 SS	2
3	TRANSITION_SIDE_LARGE	11 GAUGE 304 SS	2
4	RIB	3/8" 304 SS	1
5	EXIT FLANGE	1/2" 304 SS	1

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

16 MM TRANSITION ASSEMBLY/BOM

MATERIAL:

DWG NO.

EXPLODED VIEW

A3

WEIGHT:

SCALE:1:20

141

WELD ALL AROUND
THIS SIDE ONLY

350.00

FLANGE FACE FLUSH
TO TRANSITION FACE

WELD ALL AROUND
THIS SIDE ONLY

WELD ALL AROUND
THIS SIDE ONLY
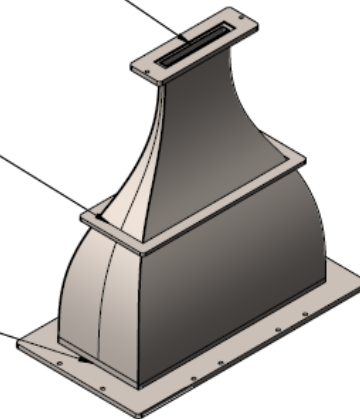
NOTE:
IMPORTANT TO MAINTAIN
GEOMETRIC SHAPE
MINIMAL WELD DISTORTION
IS REQUIRED

142

R10.00
TYP

534.00

474.00

150.00

210.00

	NAME	SIGNATURE	DATE		TITLE:	
DRAWN						
CHK'D					RIB	
APPV'D						
MFG						
Q.A			MATERIAL:		DWG NO.	A3
			3/8" 304 SS			
			WEIGHT:		SCALE:1:20	

143

[0.38]
9.53

[0.59]
15.00

[2.48]
63.10

[0.39]
⌀ 10.00
TYP

[2.39]
60.60
TYP

[0.59]
15.00

[23.87]
606.20

[26.23]
666.20
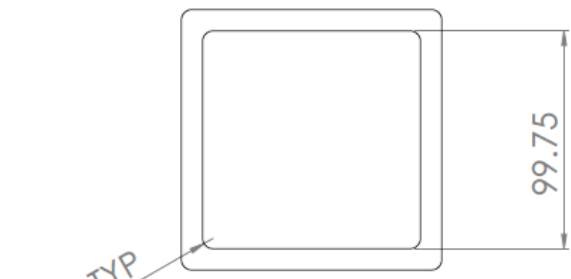
144

	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:		
DRAWN							
CHK'D					FLANGE		
APPV'D							
MFG							
Q.A		MATERIAL: 3/8" SS			DWG NO.		A3
		WEIGHT:			SCALE 1:10		

100.00

22.35

5.00

SECTION G-G

SCALE 1 : 2

12.70

152.50 TYP

325.00

228.00

206.35

G ↓ ↓ G

Ø9.00 TYP

R10.00 TYP

38.00

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					EXIT FLANGE
APPV'D					
MFG					
Q.A					

MATERIAL:
1/2" 304 SS

DWG NO.

A3

WEIGHT:

SCALE:1:20

145

16.00

750.00

255.00

NOTE:
2 PIECES REQUIRED

	NAME	SIGNATURE	DATE		TITLE:		
DRAWN							
CHK'D					TRANSITION_SIDE		
APPV'D							
MFG							
Q.A							

MATERIAL:
11 GA 304 SS

DWG NO.

A3

WEIGHT:

SCALE:1:20

146

206.35

750.00

606.35

NOTE:
2 PIECES REQUIRED

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

TRANSITION_SIDE
LARGE

MATERIAL:
11 GA 304 SS

DWG NO.

A3

WEIGHT:

SCALE:1:20

147

3/8" ACRYLIC
TOP ONLY

3 PIECES:
1/2" ACRYLIC

METRIC

148

2400.00

DRILL AND TAP
1/8" NPT X 2 ON ℄
SEE DETAIL F

SEE DETAIL E

420.00

300.00

62.50 TYP

100.00 TYP

F

F

D

D

225.00

200.00 TYP

R4.76 TYP

50.00 TYP

100.00

200.00

NOTE: 3/8" ACRYLIC

	NAME	SIGNATURE	DATE	
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:			FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
DRAWN				TITLE:
CHK'D				
APPV'D				
MFG				
Q.A			MATERIAL: 3/8" ACRYLIC	DWG NO. TEST SECTION -TOP
			WEIGHT:	SCALE:1:20

A3

149

9.53

4.76

100.00 TYP

120.00 TYP

60.00

12.50 TYP   4.77 TYP
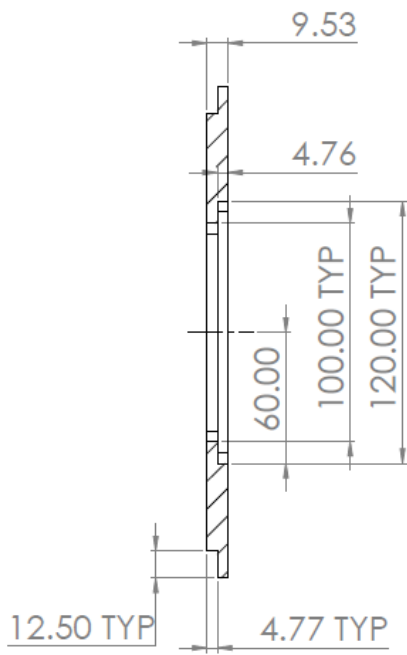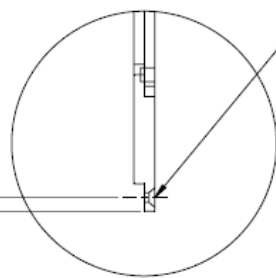
SECTION D-D
SCALE 1 : 2

BLIND TAP
1/8" NPT ⊤ 7MM

A

Ø.75 THRU
DRILL FROM DATUM A:
DRILL BREAK THRU MUST BE
OPPOSITE DATUM

SECTION F-F
SCALE 1 : 2

Ø 4.5 THRU
⌵ 82° COUNTERSINK
⊤ 3 MM X 12

E

6.25

DETAIL E
SCALE 1 : 2

150

2400.00

SEE DETAIL C

50.00 TYP

62.50 TYP

225.00

100.00 TYP

C

B

BLIND TAP M6X1
⊽ 9 MM X 4

12.50 TYP

4.77 TYP

DETAIL B
SCALE 1 : 2

⌀ 4.50 THRU-HOLE
X 12

6.25

100

200.00 TYP

DETAIL C
SCALE 1 : 2

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:		DWG NO.
			1/2" ACRYLIC		BOTTOM_TEST SECTION
			WEIGHT:		SCALE:1:20

A3

151
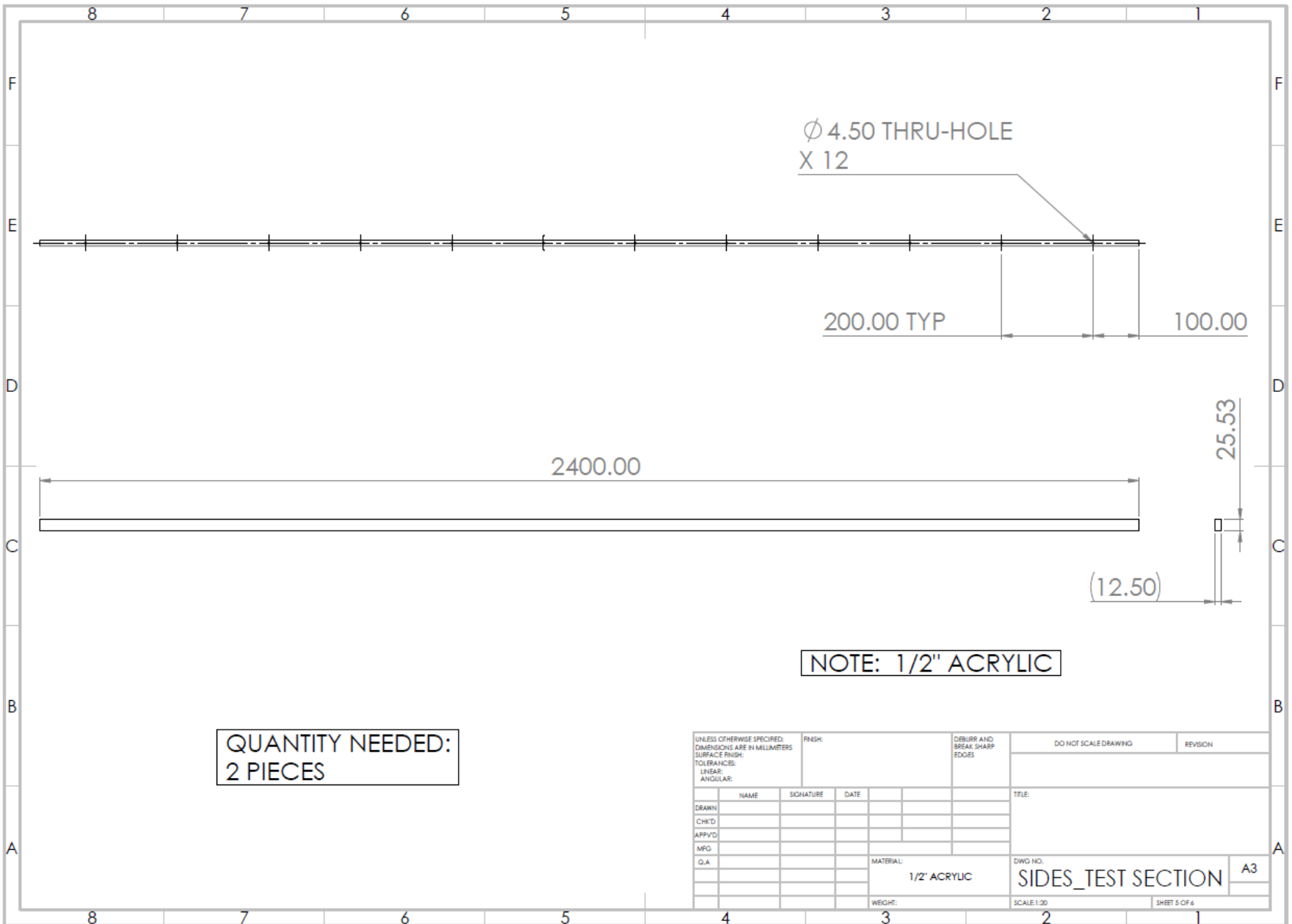
Ø 4.50 THRU-HOLE
X 12

200.00 TYP   100.00

25.53

2400.00

(12.50)

NOTE: 1/2" ACRYLIC

QUANTITY NEEDED:
2 PIECES

	NAME	SIGNATURE	DATE		TITLE:	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: 1/2" ACRYLIC	DWG NO. SIDES_TEST SECTION	A3
			WEIGHT:	SCALE:1:20	SHEET 5 OF 6

152

59.63

59.63

119.25

BLIND TAP M6X1
▽ 6.00

119.25

4.76

9.53

99.75

NOTE: 3/8" ACRYLIC

99.75

R4.76 TYP

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:		DWG NO.
			3/8" ACRYLIC		PLUG_TEST SECTION
			WEIGHT:		SCALE:1:2

A3

153
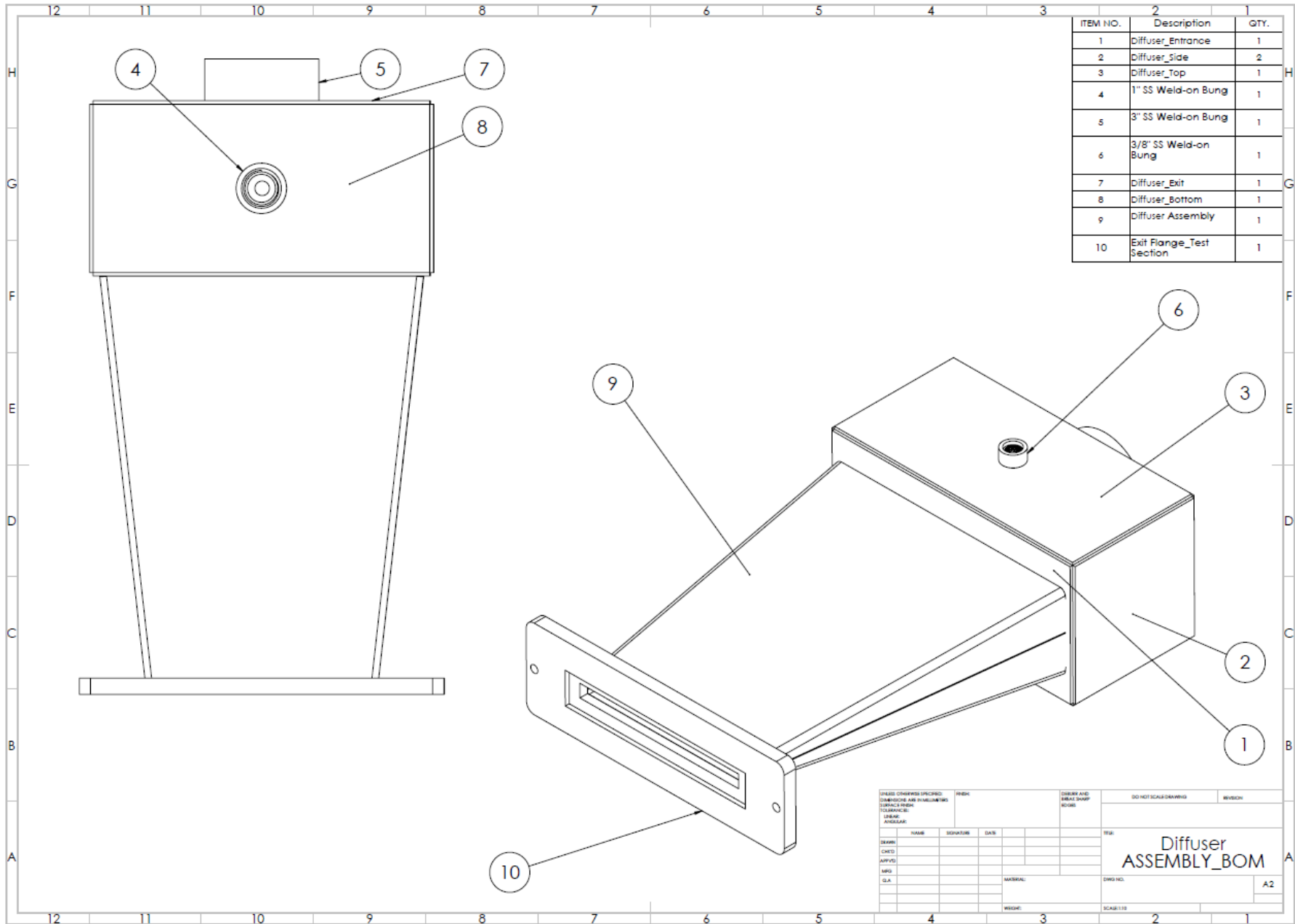
ITEM NO.	Description	QTY.
1	Diffuser_Entrance	1
2	Diffuser_Side	2
3	Diffuser_Top	1
4	1" SS Weld-on Bung	1
5	3" SS Weld-on Bung	1
6	3/8" SS Weld-on Bung	1
7	Diffuser_Exit	1
8	Diffuser_Bottom	1
9	Diffuser Assembly	1
10	Exit Flange_Test Section	1

Diffuser
ASSEMBLY_BOM

154

WELD ALL ALONG

155

94.00

360.00

16.00

208.00

288.00

156

4.47 TYP

(430.05)

7.10 TYP

4.97 TYP

196.31 TYP

(409.72)

DOWN 90° R 3

DOWN 90° R 3

DOWN 90° R 3

DOWN 90° R 3

40.46 TYP

276.30 TYP

40.96 TYP

(726.49)

TRANSITION
FLAT VIEW

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCE:
  LINEAR:
  ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

REVISION

NAME | SIGNATURE | DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A

MATERIAL:
11 GA SS

DWG NO.

A2

WEIGHT:

SCALE:1:10

157

SECTION D-D
SCALE 1 : 2

D
D

5.00

⌀9.00 X2

10.00 TYP

18.00

227.00
200.00

325.00

R10.00
TYP

39.00
16.00
12.70

158

WELD ALL AROUND

C

WELD ALL ALONG TYP

CENTER PLATE ON TRANSITON
WELD ALL AROUND
BACK SIDE ONLY

E

DETAIL C
SCALE 2 : 1

DETAIL E
SCALE 1 : 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
  LINEAR:
  ANGULAR:
	FINISH:		DEBURR AND
			BREAK SHARP
			EDGES
				DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		TITLE:
DRAWN					
CHK'D					Diffuser WELD
APPV'D					CALL-OUT
MFG					
Q.A		MATERIAL:		DWG NO.	A2
		WEIGHT:		SCALE:1:10	

159

300.00

285.00

150.00

88.00

160

300.00

150.00

⌀ 100.00
THRU HOLE

161

300.00

150.00

$\emptyset$25.00
THRU HOLE

162

300.00

150.00

⌀13.00
THRU HOLE

163

150.00

150.00

164