Abstract
The main goal of this work centers on studying the turbulent entrainment phenomenon in a viscoelastic flow. Direct numerical simulations (DNS) of a turbulent plane jet with two viscoelastic fluids (different polymer concentrations) are compared to a Newtonian flow. Therefore, it was also intended to develop and verify a computational code to simulate viscoelastic flows. Besides, at the turbulent/non-turbulent interface, conditional statistics are performed in order to study the invariants of the velocity gradient, rate-of-strain and rate-of-rotation. This quantities give precious information concerning the topology and geometry of deformation of the infinitesimal fluid elements. It was verified that polymer additives leads to an inhibition of the turbulent phenomena at the small range of scales. Therefore, the two types of fluids are very similar, from the topological and dynamic point of view, but turbulence in this type of flows is less intense.

Keywords: turbulent entrainment, viscoelasticity, plane jet, FENE-P, DNS

1. Introduction
A discover with major potential in industrial applications such as liquid transportation pipeline systems was made by B.A. Toms over 60 years ago. He found that by adding a minute amount of long-chain polymer or some kinds of surfactant additives into a turbulent flow, a dramatic frictional reduction would be achieved [1]. To interpret this turbulent drag reduction, many researchers have paid much attention to theoretical, experimental and numerical simulation studies on drag-reduction flows by additives, as proves the large literature body on the subject [2].

However, the physical mechanisms underlying the effect of dilute polymer and turbulence remain involved in a great deal of mystery. The reason is that the problem includes two poorly understood matters: turbulence and additives dynamics. Various studies have fundamental importance towards understanding the physics behind additives-turbulence interaction and, so far, they were able to offer a preliminary understanding of the flow characteristics. Drag reduction (DR) is the most well known large scale phenomena, but there is a consensus that the direct action of the polymers is on the small scales of turbulent flows [3].

More recently, some progress has been made due to detailed turbulence measures and numerical simulations of viscoelastic turbulent flows. In fact, direct numerical simulations (DNS) have played an increasingly important role in the investigation of not only this particular subject, but also turbulence itself. Many researchers have carried out DNS mainly on forced HIT (FHIT) [4] and decaying HIT (DHIT) [5], but they were mainly focused on the DR phenomenon and the characteristics of HIT with polymer additives. How the flow structures interact with polymer microstructures has still not been investigated in all its extention. This is the motivation for this work, to study the influence of the polymer additives on the microscales of a turbulent flow, namely on the turbulent entrainment process.

In order to achieve this, attention is given to the turbulent/non-turbulent (T/NT) interface separating the turbulent and the irrotational flow regions. The objective is to perform a DNS simulation of a turbulent plane jet and observe the physical mechanisms and dynamics present at this interface, the ones responsible for turbulent entrainment. The study of the invariants across this interface allows a detailed characterization of the dynamics, geometry and topology of the flow during the entrainment. They are a very useful and powerful tool and they have been extensively used in several flows configurations [6]. So by analysing their evolution some insight on the additives-turbulence interaction is expected.
This article is organized as follows. In section 2 a few notions about turbulence, turbulent entrainment and viscoelastic fluids are presented. Section 3 presents the numerical method, physical and numerical parameters used on the plane jet DNS. The verification process is described in section 4. In section 5 the main results are presented. The work ends with a review of the main results and conclusions in section 6.

2. Background

2.1. Turbulence and Turbulent Entrainment

Turbulence is present in the almost totality of the flows encountered in nature and among several industrial applications. It has long been considered of extreme importance but, despite all the significant advances in the understanding of their processes and features, it remains one of the most challenging scientific problems, eluding even a consensual definition.

In this context, the interest in study turbulent jets is related to the direct need of predicting their behaviour and influence, because they are a good object of study to improve the knowledge on the physics of turbulence.

A characteristic common to all shear flows is the existence of a sudden change from a rotational region (turbulent), to an irrotational surrounding. This change is settled by a very controversial interface, the turbulent/non-turbulent (T/NT) interface. While the jet develops streamwise, there are important exchanges of mass, momentum and scalar through this interface, spreading out the jet. This will transmit momentum to the adjoining fluid, contaminating it with vorticity and dragging mass in a phenomena known as turbulent entrainment. Despite its physics are well understood for laminar regimes, where a viscous diffusion process dominates, in the turbulent side many questions remain unanswered. Several theories have been proposed, either from experiences and theoretical studies ([7], [8]), but also from new DNS simulations ([6], [9]).

Over the years, two particular models have been considered to explain the turbulent entrainment mechanism. One says entrainment is mainly driven by the large scale motions, where large packs of irrotational fluid are involved and swallowed into the inside of the turbulent region (engulfment), then becoming turbulent due to molecular diffusion [8]. The other, known as nibling, proposes the existence of a viscous superlayer with a characteristic width of the order of the Kolmogorov microscale ($\eta$), where vorticity is diffused across that layer into irrotational flow, contaminating it, in a process similar to that happening in laminar flows [7].

However, recent experimental and numerical works have proven that the role of engulfment in the turbulent entrainment has been overestimated [10], since they showed that the amount of irrotational fluid trapped by large scale movements only accounts for approximately 10% of the total mass flux into the turbulent flow. Nevertheless, it is still assumed that large scale motions play an important role in the whole process, i.e., although turbulent entrainment is caused primarily by small scale eddy motions, the entrainment and mixing rates are determined largely by the large scales flow vortices.

From the several methods and approaches used to analyse this phenomenon, the study of the invariants in turbulent flows has attracted much attention on the last years [6]. The invariants of the velocity gradient, rate-of-strain and rate-of-rotation tensors are scalar quantities whose values are independent of the orientation of the coordinate system and contain information concerning the rates of vortex stretching and rotation, and on the topology and geometry of deformation of the infinitesimal fluid elements. Their definitions, relationships and physical meanings can be found in [6]. For this work, the evolution of six invariants was considered, being the second and third invariants of the velocity tensor ($Q, R$), the second and third invariants of the rate-of-strain tensor ($Q_S, R_S$) and the only invariant of the rate-of-rotation ($Q_W$).

The previous mentioned invariants are analysed in joint probability density functions (PDFs) combining two invariants. The combinations consist on the maps of ($R, Q$), ($R_S, Q_S$) and ($Q_W, −Q_S$). These are showed in figs. 1(a) to 1(c) along with the physical meaning associated to each particular location.

2.2. Viscoelastic Fluids

The use of viscoelastic fluids, in particular dilute polymeric solutions, has been studied by researchers for both practical and fundamental proposes. This extensive research activity produced sufficient experimental evidence to conclude that the underlying physical mechanisms of DR involve dynamical interactions between polymers and turbulence. Two results provide the basic evidence. The first is that laminar pipe flow of dilute polymer solutions shows no significant differences in the skin friction (or other flow characteristics) compared with laminar pipe flow of Newtonian fluids. The second is that, for a fixed pipe diameter, the Reynolds number, $Re$, at which DR is first observed depends on the number of monomers
in the macromolecule. This implies an incipient interaction because, in general, turbulence dynamics depend fundamentally on \( Re \) and polymer dynamics depend fundamentally on the number of monomers [11].

Detailed explanations for the onset of DR can generally be divided into two classes, based on the proposed effects of polymer stretching on the flow. The first class focuses on viscous effects ([12], [13]), while the second refers to the elastic effects ([14], [15]). The viscous explanation claims that the effect of polymer stretching in a turbulent flow produces an increase in the effective viscosity. It is argued that a large increase occurs just outside the viscous sublayer and it will suppress turbulent fluctuations, enlarging the buffer-layer thickness and reducing the wall friction in wall-bounded turbulent shear flows [12].

On the other hand, the elastic theory [15] postulates that the elastic energy stored by the partially stretched polymers is an important variable and the increase in the effective viscosity is small and inconsequential. It says that when the cumulative elastic energy stored by the partially stretched polymers becomes comparable with the kinetic energy in the buffer layer, at some turbulent length scale larger than the Kolmogorov scale, the usual energy cascade is terminated prematurely and scales below cutoff are believed to behave elastically [14]. These effects yield a thicker buffer layer and subsequent DR.

Despite the two classes of explanations appear fundamentally different, both have merit when compared to experimental data. At first sight, this implies an inconclusive finding, but the issue is more complicated because an elastic effect can formally be interpreted in terms of a corresponding viscous effect [16]. This is best observed and explained from model systems of a polymer, such as the FENE-P (finite elastic non-linear extensibility-Peterlin).

The FENE dumbbell is an elementary non-linear kinetic model in which the polymeric part is described by two identical beads connected through an entropic spring (fig. 2(a)). The model captures two essential characteristics of a linear polymer: orientability and stretchability. These properties are essential to describe rheological properties of the polymer solution [11].

The beads are advected through the flow and deformed by the forces due to straining of the flow. Advection is related to the motion of the center of mass of the dumbbells, while deformation changes the dumbbell configuration, i.e., the orientation and the separation distance of the beads. The polymeric dynamics are then described by the evolution of the vector \( \mathbf{r} \) that connects the two beads, as can be seen in fig. 2(a).

In the FENE-P model, the polymer is characterized by three parameters: the relaxation time \( \lambda_p \), the length parameter \( L \) and the polymer viscosity \( \mu_p \), which is related to polymer concentration. Hence, the polymer contribution \( \tau_p \) to the stress tensor is given by

\[
\tau_p = \frac{\mu_p}{\lambda_p} [f(r)C - I],
\]

where \( f(r) \) is the Peterlin function, \( C \) is the conformation tensor and \( I \) the identity matrix. The conformation tensor is defined as

\[
C = \frac{\langle rr^T \rangle}{\langle r^2 \rangle_{eq}},
\]
being \( \mathbf{r} \) the instantaneous orientation of a polymer dumbbell and \( \langle r^2 \rangle_{eq} \) is the square of the equilibrium separation distance.

The issue of whether the FENE-P model is an adequate representation of the FENE model in the context of turbulent flow has also been investigated by Zhou and Akhavan [23]. The conclusion was that the model was accurate in steady state, incurring in some errors at transient elongational flows. The limitations are primarily related to the description of polymer molecule. Usually consisting of \( N \approx 10^5 \) monomers, a polymer molecule is reduced to a single dumbbell. In addition, dumbbell models do not incorporate polymer-polymer interactions, which can be important even for dilute polymer solutions.

Despite its inherent limitations, FENE-P model has predicted results, for different aspects of drag reduction phenomenon, that are qualitatively consistent with experiments. Besides, due to high computational cost associated with the stochastic models (FENE and FENE-P chain), is the only viable choice for high resolution turbulent flows at present.

Within the framework of the FENE-P model, the elastic energy stored by a stretched polymer is proportional to the trace of the conformation tensor, \( Tr(\mathbf{C}) = C_{xx} + C_{yy} + C_{zz} \). If the problem is approached from the elastic theory perspective, the transport equation for the elastic energy can be studied to understand the energy transfer between the polymers and the flow [16]. Alternatively, by taking the viscous theory point of view, Benzi et al. [24] found that an important component of the conformation tensor is \( C_{yy} \), which appears in the momentum and kinetic energy equations as an effective viscosity.

3. Numerical Tools

In order to study the additives-turbulence interaction a DNS of a turbulent plane jet is performed. For a viscoelastic fluid, an additional polymer stress term is included to the Navier-Stokes equation and the fluid rheology is described by the FENE-P model. The full set of governing equations for dilute polymer solutions in a plane jet are:

\[
\nabla \cdot \mathbf{u} = 0; \quad \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \frac{1}{\rho} \nabla \cdot \mathbf{T}^{[s]} + \frac{1}{\rho} \nabla \cdot \mathbf{T}^{[p]};
\]

\[
\frac{\partial \mathbf{C}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{C} = \mathbf{C} \cdot \nabla \mathbf{u} + \nabla \mathbf{u}^T \cdot \mathbf{C} - \frac{1}{\lambda_p} \left[ f(r) \mathbf{C} - \mathbf{I} \right].
\]

The above equations (3 – 5) are valid at each point of a cartesian reference system with coordinates \( \mathbf{x} = (x, y, z) \) and at the time instant \( t \). Also, \( \mathbf{u}(\mathbf{x}, t) \) is the velocity vector \( \mathbf{u} = (u, v, w) \), \( p(\mathbf{x}, t) \) is the local pressure field, \( \rho \) is the fluid density, \( \mathbf{T}^{[s]} = 2 \mu^{[s]} S \) is the Newtonian stress tensor due to the solvent, \( \nu^{[s]} \) is the solvent kinetic viscosity and \( S = (\Gamma_{ij} + \Gamma_{ji})/2 \) is the rate of strain tensor, with \( \nabla \mathbf{u} = \Gamma_{ij} = \partial u_j / \partial x_i \) and \( \nabla \mathbf{u}^T = \Gamma_{ji} \). Moreover \( \mathbf{T}^{[p]} = (\rho \nu^{[p]} / \lambda_p) (f(r) \mathbf{C} - \mathbf{I}) \) is the additional elastic stress tensor due to polymers, \( \nu^{[p]} \) is the polymer viscosity, \( \lambda_p \) is the polymer relaxation time, \( \mathbf{C} \) is the polymer conformation...
tensor and \( I \) is the unit tensor. In the FENE-P model, \( f(r) = (L^2 - 3)/(L^2 - R^2) \) ensures the finite extensibility, where \( R = \sqrt{\text{trace}(\mathbf{C})} \) and \( L \) are the extension length and the maximum possible extension of polymers, respectively.

The polymer viscosity \( \mu[p] \) is obtained from a dimensionless number representing the polymer solution concentration, \( \beta = \mu[p]/(\mu[\text{sol}] + \mu[p]) \).

To solve the previous equations, a pseudo-spectral method is used for spacial discretization of Eq.(3) and Eq.(4), while for Eq.(5) a second-order central difference scheme is applied except for the convective term. This term is discretized by using a second-order Kurganov-Tadmor (KT) scheme developed by Vaithianathan et al., which can be seen in [17]. The temporal advancement is made with an explicit third-order Runge–Kutta time stepping scheme. The simulation was fully dealised by using the 3/2 rule.

The initial condition consists of an hyperbolic-tangent velocity profile, that was also used as the inlet condition in several other simulations [6]. A three component velocity fluctuating ‘spectral noise’ was superimposed to the mean velocity profile through a proper convolution function that imposes the velocity fluctuations in the initial shear layer region of the jet. The spectral noise used here is the same used in [6]. A relatively high amplitude spectral noise was added (8%) in order to speed up the transition mechanism and allow the flow to quickly reach a fully developed turbulent state. Besides, the addition of a high \( H/\theta_0 \) ratio \( (H/\theta_0 = 35) \) and a high Reynolds number \( Re_H = (U_3 - U_1)H/\nu = 3200 \) further reduce the time spent during the transition phase and does not affect the dynamics of the self-similar fully developed turbulent state.

The computational domain measures \((L_x, L_y, L_z) = (4H, 6H, AH)\) along the streamwise \((x)\), normal \((y)\) and spanwise \((z)\) jet directions. The grid size consists in \((N_x \times N_y \times N_z) = (256 \times 384 \times 256)\) grid points. Periodic boundary conditions are assigned to all the three directions.

4. Verification

Since the code was already validated for the velocity fields [6], the algorithm to obtain de deformation tensor used herein is the thing left for analysis. The validation was performed in two ways. One consisted in comparing the numerical results with an analytical solution for a stationary, fully developed laminar flow. In the other, numerical simulations on decaying homogeneous isotropic turbulence (DHIT) were carried out and the results compared to similar simulations present in the literature [18].

The analytical solution developed was based on the channel flow analysed by Pinho et al. [25], with the proper changes for the case in study, a plane jet. A different inlet profile, in a shape of a saw, was also considered:

\[
\mathbf{u} = \begin{cases} 
\frac{U_2+U_1}{2} + (U_2 - U_1) \left(1 + \frac{2y}{3H}\right) & \text{if } y < -\frac{3H}{2} \\
U_2 - (U_2 - U_1) \left(1 + \frac{2y}{3H}\right) & \text{if } -\frac{3H}{2} \leq y \leq \frac{3H}{2} \\
U_1 + (U_2 - U_1) \left(\frac{y}{3H} - \frac{1}{2}\right) & \text{if } y > \frac{3H}{2}
\end{cases}
\]  

(6)

This allows a constant value for the velocity derivative except on the discontinuities.

The analysis started by performing the same simulation on each direction, by changing the streamwise direction (first \( x \), then \( y \) and \( z \)), and evaluate the error. This error was defined as the maximum difference between the analytical and the numerical solutions. The results showed that the code quickly approaches the analytical solution and, after stabilization, the error is neglectable. Then, a few parameters were varied and their influence on the value of the conformation field was assessed. It was possible to conclude that higher values of polymer relaxation time correspond a conformation field with higher magnitude. Besides, the variation of the polymer maximum extension produced no significative differences on the values and profiles of the conformation tensor elements. This two results are in good agreement with the expectations that result from the analysis of the conformation tensor equation.

Finally, regarding the DHIT simulations, it was possible to reproduce the results obtained by Zhang et al. [18]. The temporal evolution of several physical quantities like the Taylor microscale, the energy dissipation rate and the total kinetic energy (among others) appear to be very similar to the ones present on the previous mentioned article. Moreover, the turbulent kinetic energy spectra were also very much alike.

This small battery of tests certifies the implementation method used.

5. Results

The parameters for all simulations are presented in table 1.

5.1. T/NT interface detection

the T/NT interface is defined by using the vorticity norm \( \omega = (\omega_1^2) \). It was observed that the detection threshold of \( \omega = 0.7U_2/H \) best delineated the vortical regions. Figure 3 shows contours of
vorticity modulus corresponding to this threshold in an \((x,y)\) plane of the jet at \(T/T_{ref} = 12\), for each simulation. This instant is located in the far-field and in fully developed turbulent regime. It can be seen that the T/NT interface is strongly contorted and between Newtonian and viscoelastic fluid there are no major large scale differences, apart from the more intense vortices in the Newtonian fluid.

Table 1: Plane jet simulations parameters

<table>
<thead>
<tr>
<th>Simulation</th>
<th>(N_x \times N_y \times N_z)</th>
<th>(\nu)</th>
<th>(L)</th>
<th>(\lambda_p)</th>
<th>(\beta)</th>
<th>(C_0^\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET1</td>
<td>256\times384\times256</td>
<td>10^{-2}</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>JET2</td>
<td>256\times384\times256</td>
<td>10^{-2}</td>
<td>100</td>
<td>0.1</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>JET3</td>
<td>256\times384\times256</td>
<td>10^{-2}</td>
<td>100</td>
<td>0.1</td>
<td>0.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

To study the turbulent entrainment, conditional statistics are analysed in relation to the location of the interface envelope by using a procedure similar to one described in [6].

5.2. Conditional mean vorticity

Figure 2(b) shows mean conditional profiles of \(\langle|\omega_z|\rangle_I\) (non-dimensionalized by \(U_2/H\)) in relation to the distance from the T/NT interface \(y_I\), which is non-dimensionalized by the value of the Kolmogorov microscale at the jet shear layer. This quantity shows a sharp transition from the irrotational to the turbulent zone, in both types of fluid, and a peak very close to the interface. However, it is perceptible that this peak value (and also inside the turbulent region) is lower for viscoelastic fluids. This allows one to do a first conclusion, that the turbulence in a fluid with polymer additives is less intense.

Based on this profile, three particular locations in relation to the distance from the T/NT interface are considered: \(y_I/\eta = 0.0\), exactly at the T/NT interface, \(y_I/\eta = 19.9\), which is close to the point of maximum \(\langle|\omega_z|\rangle_I\), and \(y_I/\eta = 64.7\), a point that is already well inside the turbulent zone.

5.3. Analysis of the invariants \(Q_W\) and \(Q_S\)

In fig. 4(a) are presented conditional mean profiles of the second invariant of the rate-of-strain tensor \(Q_W\) and the invariant of the rate-of-rotation tensor \(Q_S\) in relation to the distance from the T/NT interface, along with the profile for the vorticity component \(\langle|\omega_z|\rangle_I\) and the symbols marking the three locations mentioned before. The analysis of this quantities helps to understand the geometry of the dissipation.

The interesting thing here is that the polymer influence does not manifest itself until crossing the T/NT interface, since the mean profile evolution is exactly the same for \(y_I/\eta < 0\), regardless the type of fluid. Even for \(\langle Q_S \rangle_I\), that begins to grow before the interface, in the viscoelastic fluid the same behavior is verified. However, as soon as the T/NT interface has been crossed, the polymer immediately alters the evolution of both \(\langle Q_S \rangle_I\) and \(\langle Q_W \rangle_I\), it causes a lower increase rate. Since \(\langle Q_S \rangle_I = -(S_{ij}S_{ij})_I/2\) is proportional to the dissipation rate, this means that the mechanism of viscous dissipation is altered...
5.4. Analysis of the invariants \( Q_S \) and \( R_S \)

In order to analyse the geometry of straining of the fluid elements, the second and third invariants of the rate-of-strain tensor \( Q_S \) and \( R_S \) are investigated near the T/NT interface. Figure 4(b) displays mean profiles of these invariants in relation to the distance from the T/NT interface and the profile for \( \langle |\omega_z| \rangle \). The evolution of the mean invariant \( \langle Q_S \rangle \) was already described. As for \( \langle R_S \rangle \), it starts by being negligible for \( y_I/\eta < 0 \), but when the T/NT interface is crossed, this quantity starts to grow until reach its interval of turbulent values. By adding the polymer, the increase rate of \( \langle R_S \rangle \) becomes even lower, diminishing the deformation of the fluid elements. In fig. 5(b) the trajectories of the mean values of \( \langle Q_S \rangle \) and \( \langle R_S \rangle \) are shown, in their associated phase map. For the entire flow region, the invariants are always in the zone of \( \langle R_S \rangle > 0 \) and \( \langle Q_S \rangle < 0 \), meaning that the mean flow geometry is related with expansion of the fluid elements. In the irrotational region, the mean flow topology is \( 3 : 1 : -4 \) (sheetlike structures) and then starts changing to \( 2 : 1 : -3 \) between the T/NT interface and the point of maximum \( \langle |\omega_z| \rangle \). However, just before this location, the flow geometry turns again into \( 3 : 1 : -4 \) and there it stays
until well inside the turbulent region. As before, associated to the viscoelastic fluids are lower values of \((Q_{S})_T\) (discussed in the previous section) and \((R_{S})_T\), but the invariants trajectory is proportionally the same. This means that the fluid elements deform less but in same way and shape on both fluids.

5.5. Analysis of the invariants \(Q\) and \(R\)

The second and third invariants of the velocity gradient tensor \(Q\) and \(R\) allows to analyse the relation between the flow topology and dynamics. Conditional mean profiles of this quantities in relation to the T/NT interface are shown in fig. 4(c). Once again, the mean profile of \(\langle|\omega_2|\rangle_1\) and the symbols marking \(y_1/\eta = 0, 19.9, 64.7\) are also presented.

In the irrotational region, the conditional mean profile of \(\langle Q \rangle_1\) takes negative values (\(\langle Q \rangle_1 < 0\)). Since \(Q = \langle \omega_i \omega_j - 2 S_{ij} S_{ij} \rangle / 4\) and in this region there is virtually no vorticity, the evolution of \(\langle Q \rangle_1\) is dominated by the strain product \((\langle Q \rangle_1 \approx \langle Q_{S} \rangle_1)\). Therefore, its evolution is not surprising. Just after the T/NT interface, \(\langle Q \rangle_1\) reaches a minimum of \(\langle Q \rangle_1 \approx -2.0, -1.9\) and \(-1.7\) at \(y_1/\eta \approx 8\) respectively for JET1, JET2 and JET3. From this point onward, the enstrophy dominates over strain product, because it grows at a lower rate (see \((R_{S})_T\)) than the vorticity (hence enstrophy), and a maximum at about \(y_1/\eta \approx 20\) is achieved. Next, a decrease is verified. Differently, the invariant \(R = -[S_{ij} S_{ik} S_{kj} + (3/4)\omega_i \omega_j S_{ij}]/3\) is negligible until just before the T/NT interface. At \(y_1/\eta = 15\), \(\langle R \rangle_1\) begins to be non-negligible \((\langle R \rangle_1 \approx 0.1(U_2/H)^3)\), due to strain production (the vorticity is still virtually zero at this point). After the T/NT interface, \(\langle R \rangle_1\) reaches a positive maximum of \(\langle R \rangle_1 \approx 0.8(U_2/H)^3, 0.7(U_2/H)^3\) and \(0.6(U_2/H)^3\) at \(y_1/\eta \approx 6\), respectively for simulations JET1, JET2 and JET3 (the higher polymer concentration, lower the value). Afterwards, \(\langle R \rangle_1\) decreases to a minimum \((\langle R \rangle_1 \approx -1.9(U_2/H)^3, -1.4(U_2/H)^3\) and \(-1.4(U_2/H)^3\) at \(y_1/\eta \approx 18, 16\) and \(14\), respectively for JET1, JET2 and JET3. An increase to zero would now be expected, but instead fluctuations around a negative value are visible.

Figure 5(c) displays the trajectory of the mean values of \(\langle Q \rangle_1\) and \(\langle R \rangle_1\) in the respective phase map. In the irrotational flow region, the mean invariants stay at the origin \((\langle R \rangle_1 \approx 0\) and \(\langle Q \rangle_1 \approx 0\)) of the map. Approaching the T/NT interface makes the invariants to move away and become more distant from the origin, towards the region of \(\langle R \rangle_1 > 0\) and \(\langle Q \rangle_1 < 0\), associated with straining of fluid elements. After the T/NT interface, the mean flow topology quickly moves to the region dominated by vortex stretching \((\langle R \rangle_1 < 0\) and \(\langle Q \rangle_1 > 0\)). The point of maximum \(\langle |\omega_2|\rangle_1\) is located in this area, indicating a relation with maximum values of vortex stretching that occur during the turbulent entrainment. For last, the mean invariants go back to the region near the origin of the phase map, as expected, since the mean values of \(\langle R \rangle_1 < 0\) and \(\langle Q \rangle_1 > 0\) in the center of the jet shear layer behave as isotropic turbulence (are near zero).

However, in the figures there is a large dispersion of points on both sides of the map which makes very difficult to see the trajectory. A solution for this problem is to increase the number of samples used in the conditional statistics. In the fully developed turbulent regime, each instantaneous field is statistically equivalent. Therefore, by taking other fields it would still be in the same turbulent regime and the trajectory of the mean values would be better converged. Nevertheless, a few thoughts on the differences between viscoelastic and Newtonian fluids can be withdrawn. One more time, the polymer additives restrain the normal development of the mean conditional values, but opposed to the previous quantities, the differences are less significative. The maximum and minimum values are indeed lower and higher, respectively, within a viscoelastic fluid, but the evolution is pratically the same, except inside the turbulent zone, where the convergence is not very good.

6. Conclusions

The introduction of polymer additives in a turbulent flow does not cause dramatic changes. The numerical results from the present work showed that the turbulent jet maintains the most part of its characteristics. However, it was possible to detect some subtle yet important discrepancies. From the large scales point of view, the vorticity contour plots showed that externally the flows are very similar. The difference was on the magnitude of the vortices surrounding the T/NT interface. For the viscoelastic fluids, vorticity was lower.

Analysing the evolution across the T/NT interface of several conditional mean profiles, it was possible to verify that the same evolutions and tendencies were present in the viscoelastic fluids, but the transitions were smoother for the viscoelastic case.

In this way, the polymer chains can be interpreted as a second dissipation mode, different from the classic viscous mode. They have the capability to absorb and inhibit the steep gradients that are predominant at the small scale range.

Finally, it is also important to mention that a small change on the polymer concentration causes a considerable change between two viscoelastic flows.
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References


