A Mean Flow Model for Polymer and Fiber Turbulent Drag Reduction

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Abstract:
We present a one-parameter model that fits quantitatively the mean velocity profiles from experiments and numerical simulations of drag-reduced wall-bounded flows of dilute solutions of polymers and non-Brownian fibers in the low and modest drag reduction regime. The model is based on a viscous mechanism of drag reduction, in which either extended polymers or non-Brownian fibers increase the extensional viscosity of the fluid and thereby suppress both small and large turbulent eddies and reduce momentum transfer to the wall, resulting in drag reduction. Our model provides a rheological interpretation of the upward parallel shift S^+ in the mean velocity profile upon addition of polymer, observed by Virk. We show that Virk's correlations for the dependence on polymer molecular weight and concentration of the onset wall shear stress and slope increment on the Prandtl-Karman plot can be translated to two dimensionless numbers, namely an onset Weissenberg number and an asymptotic Trouton ratio of maximum extensional viscosity to zero-shear viscosity. We believe that our model, while simple, captures the essential features of drag reduction that are universal to flexible polymers and fibers, and, unlike the Virk phenomenology, can easily be extended to flows with inhomogeneous polymer or fiber concentration fields.

Zusammenfassung:
Wir präsentieren ein 1-Parameter-Modell, das quantitativ die mittleren Geschwindigkeitsprofile aus Experimenten und numerischen Simulationen von strömungswiderstandsreduzierenden, durch Wände begrenzte Strömungen von verdünnten Lösungen aus Polymeren und nicht-Brownschen Fasern für niedrige und mittlere Strömungswiderstände wiedergibt. Das Modell basiert auf einem viskosen Mechanismus der Widerstandsreduktion, in dem entweder ausgedehnte Polymere oder nicht-Brownsche Fasern die Dehnviskosität des Fluids erhöhen und dadurch kleine und große turbulente Wirbel unterdrücken und den Impulstransfer zur Wand reduzieren, was in eine Verminderung des Strömungswiderstandes resultiert. Unser Modell beinhaltet eine rheologische Interpretation der parallelen Aufwärtsverschiebung S+ im mittleren Geschwindigkeitsprofil bei Zugabe des Polymers, die von Virk beobachtet wurde. Wir zeigen, dass die Korrelationen von Virk für die Abhängigkeit vom Molekulargewicht des Polymers und der Konzentration der anfänglichen Wandscherspannung und der Steigung in der Prandtl-Karman-Auftragung in zwei dimensionslose Größen übertragen werden können, nämlich in eine Weissenbergzahl für den Beginn und in ein asymptotisches Trouton-Verhältnis der maximalen Dehnviskosität zur Schernullviskosität. Wir glauben, dass unser Modell, obgleich es einfach ist, die wesentlichen Merkmale der Strömungswiderstandsreduktion beinhaltet, die allgemein für flexible Polymere und Fasern gelten, und, im Gegensatz zur Phänomenologie von Virk, in einfacher Weise auf Strömungen mit inhomogenen Konzentrationsfeldern von Polymeren und Fasern erweitert werden kann.

Résumé:
Nous présentons un modèle à un paramètre qui s'ajuste quantitativement aux profils de vélocité moyenne provenant d'expériences et de simulations numériques d'écoulements avec réduction de résistance et sans glissement aux parois pour des solutions diluées de polymères et de fibres non Browniennes, dans le régime de faible réduction de résistance. Le modèle est basé sur un mécanisme visqueux de la réduction de résistance, dans lequel soit les polymères étirés, soit les fibres non Browniennes augmentent la viscosité extensionnelle du fluide, et ainsi suppriment les bords de grande ou petite turbulence, et réduisent le transfert de force vers les murs, ce qui a pour effet une réduction de la résistance. Notre modèle fournit une interprétation rhéologique du déplacement parallèle vers le haut S+ pour le profile de vélocité moyenne, observé par Virk lors de l'addition du polymère. Nous montrons que les corrélations de Vick établies pour la variation de l'apparition de contrainte aux parois et de l'augmentation de la pente sur le graphe de Prandtl-Karman en fonction du poids moléculaire du polymère et de la concentration en polymère, peuvent être réduites à deux nombres adimensionnels, à savoir un nombre de Weissenberg critique pour l'apparition de la contrainte, et un ratio de Trouton asymptotique de la viscosité extensionnelle maximum sur la viscosité statique. Nous pensons que notre modèle, malgré sa simplicité, capture les caractéristiques essentielles de la réduction de résistance qui sont universelles pour les polymères flexibles et les fibres, et, contrairement à la phénoménologie de Virk, peut aisément être étendue à des écoulements avec des champs non homogènes de concentration en polymère ou fibre.

Key words: drag reduction; polymer; fiber; Virk phenomenology; direct numerical simulation; turbulence

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