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Motion of a Taylor bubble in a realistic shear-thinning fluid

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ABSTRACT

This talk will focus on the motion of a gaseous Taylor bubble in a capillary tube. Although the dynamics of a bubble in a Newtonian liquid has been the subject of several studies since the seminal works Taylor and Bretherton, the case where the fluid exhibits a shear-thinning behaviour is much less understood. To fill this gap, we derive a lubrication model in the film region to identify the scaling laws for the bubble speed and the film thickness as a function of the Ellis number and the degree of shear-thinning. Our model identifies a universal scaling law for the effective viscosity that accounts for the interplay of the zero-shear-rate and shear-thinning effects. After discussing the features of the front and rear menisci, we present an analysis of the recirculation vortexes ahead of the bubble. In the final part of the talk, we show the results of recent numerical simulations that validate the proposed theory and suggest a strategy to account for the effect of finite capillary numbers on the scaling law for the film thickness in the case of shear-thinning fluids.

Videos to this article can be found online at https://doi.org/10.1016/j.sctalk.2022.100080.

Figures and tables

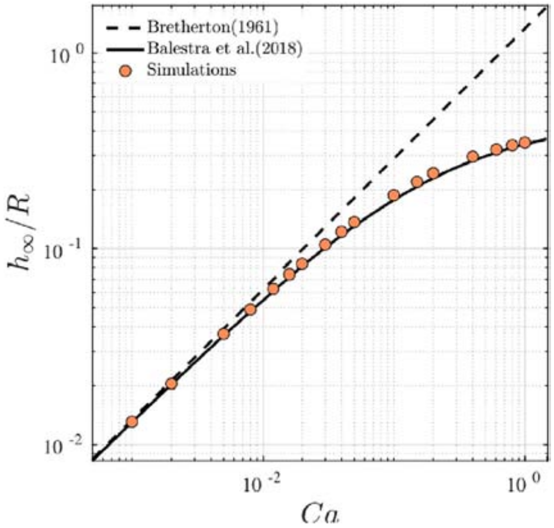

Fig. 1. The trend of the film thickness around a Taylor bubble in regimes where gravity and inertia can be neglected (Newtonian fluid). The seminal work of Bretherton [1] provides the scaling of the film thickness in the limit of small capillary numbers. The correlation by Balestra et al. [2] captures the data up to finite capillary numbers.

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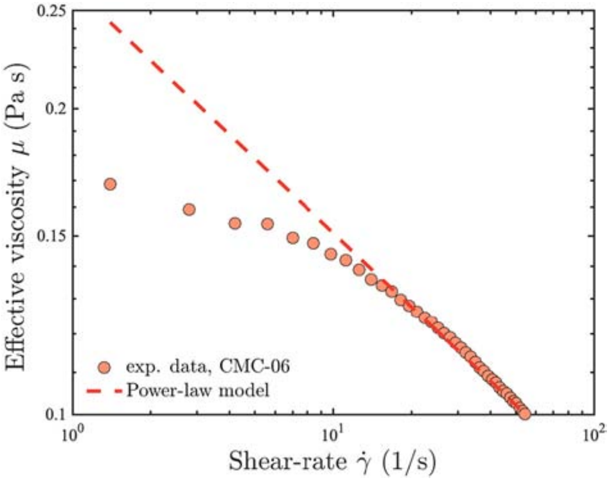

Fig. 2. Rheological characterization of a shear-thinning solution. Realistic shear thinning fluids exhibits a Newtonian behaviour at small shear-rates but the widely used power-law model does not capture this limiting behaviour.

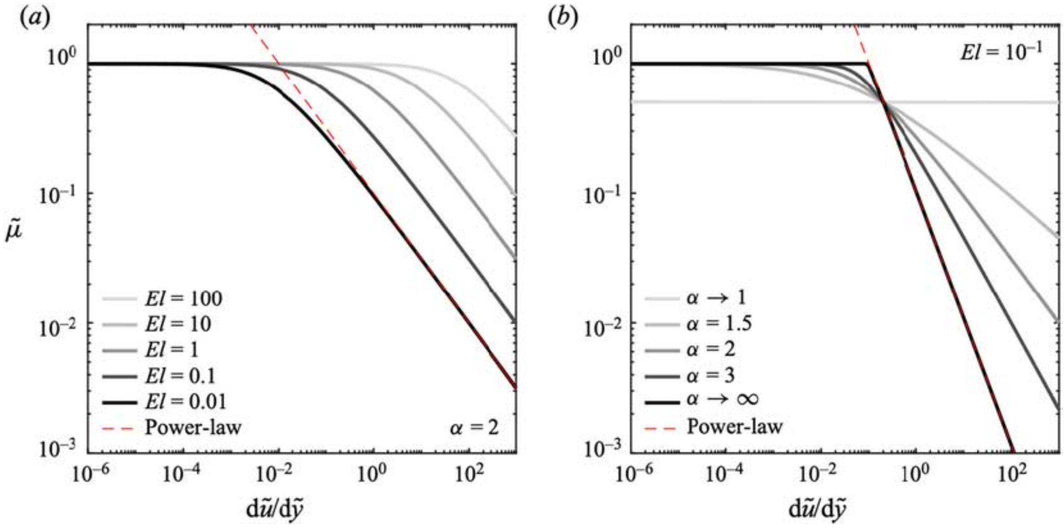

Fig. 3. The Ellis viscosity model. Evolution of the dimensionless effective viscosity as a function of the shear rate and the rheological parameters of the Elis viscosity model. The power-law limit is plotted as a red-dashed line. The picture has been taken from Picchi et al. [3], with permission from Cambridge University Press. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

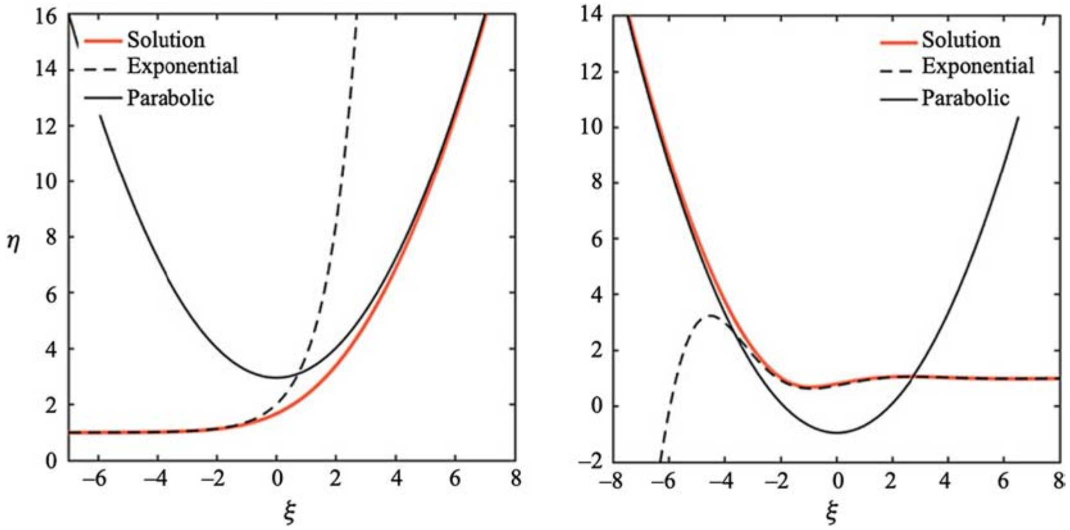

Fig. 4. Numerical solution of the film equation for an Ellis fluid for both the front and the bubble rear. Close to the uniform film region the profile follows an exponential behaviour while, far from it, it follows a parabolic trend. The picture has been taken from Picchi et al. [3] with permission from Cambridge University Press.

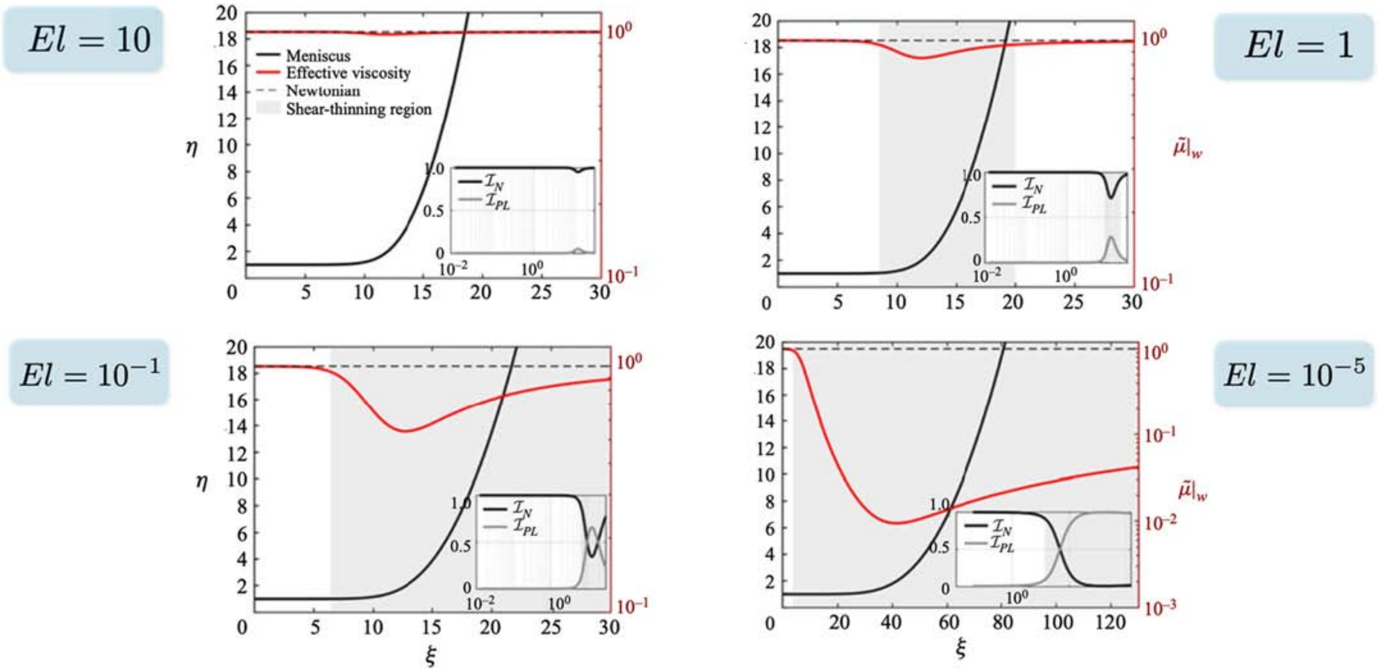

Fig. 5. Identification of the Newtonian and the shear-thinning regions in the bubble front as a function of the Ellis number. The insets show the weight of the Newtonian and the shear-thinning terms in the film equation. The pictures have been taken from Picchi et al. [3] with permission from Cambridge University Press.

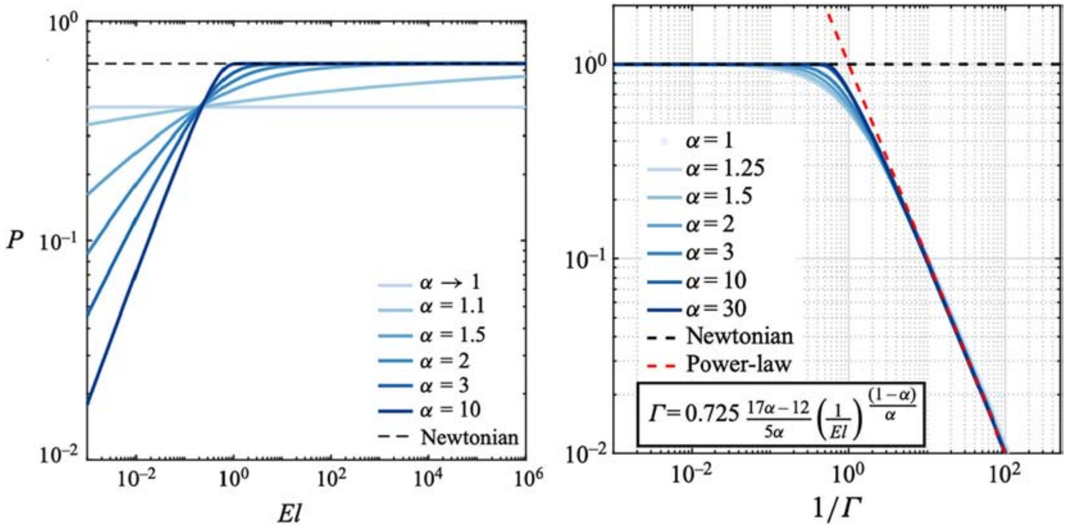

Fig. 6. Master curve for the effective viscosity of the system. (Left) Evolution of the coefficient which characterizes the curvature of the film thickness in the parabolic region of the bubble front. (Right) Collapsing of all the viscosity curves around the master curve for the effective viscosity. The pictures have been taken from Picchi et al. [3] with permission from Cambridge University Press.

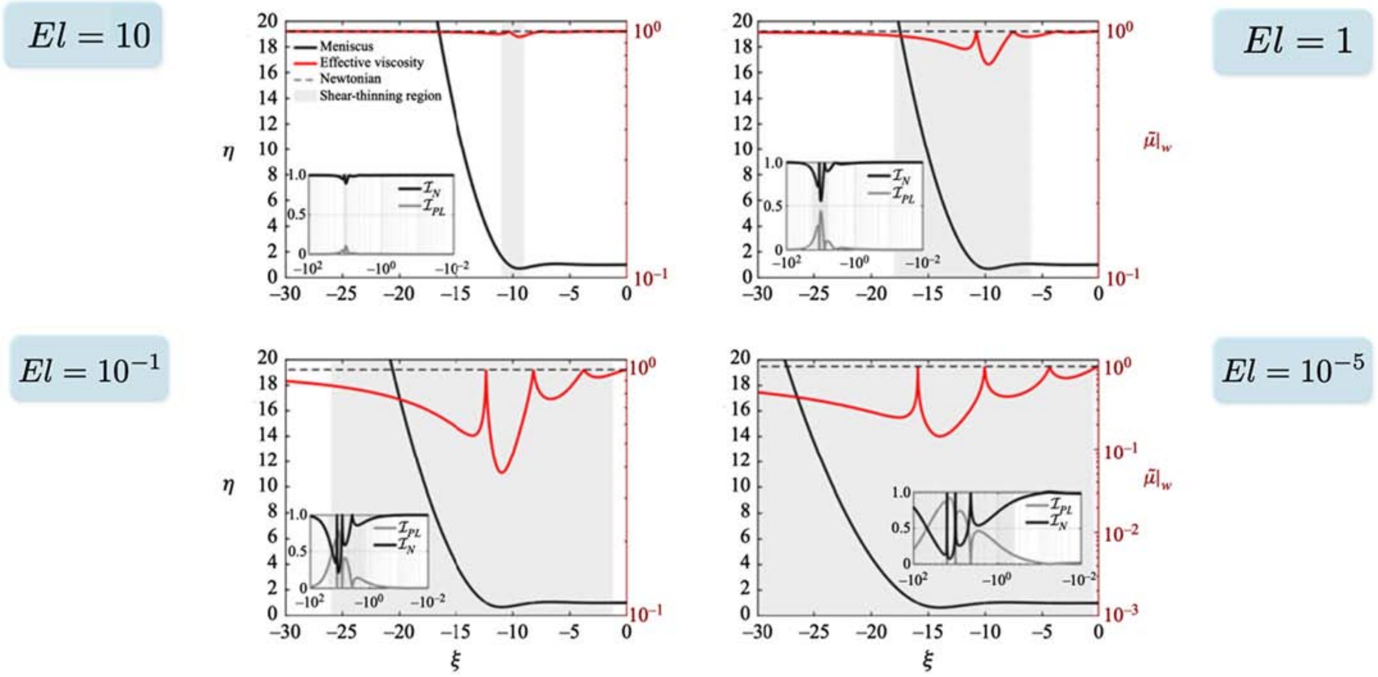

Fig. 7. Identification of the Newtonian and the shear-thinning regions in the bubble rear as a function of the Ellis number. The insets show the weight of the Newtonian and the shear-thinning terms in the film equation. The pictures have been taken from Picchi et al. [3] with permission from Cambridge University Press.

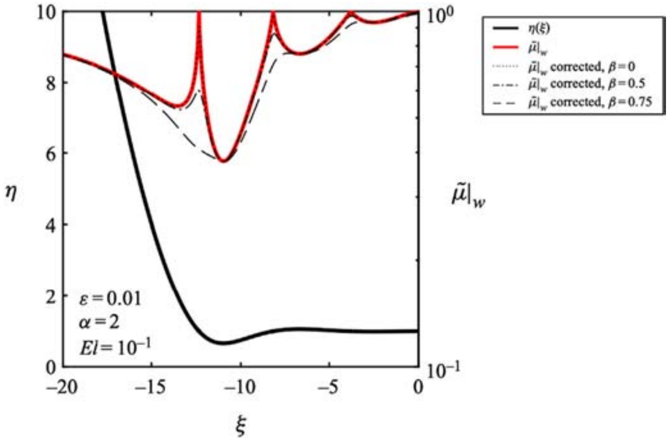

Fig. 8. Spikes of the wall-effective viscosity predicted by the film equation from Picchi et al. [3]. The picture has been taken from Picchi et al. [3] with permission from Cambridge University Press.

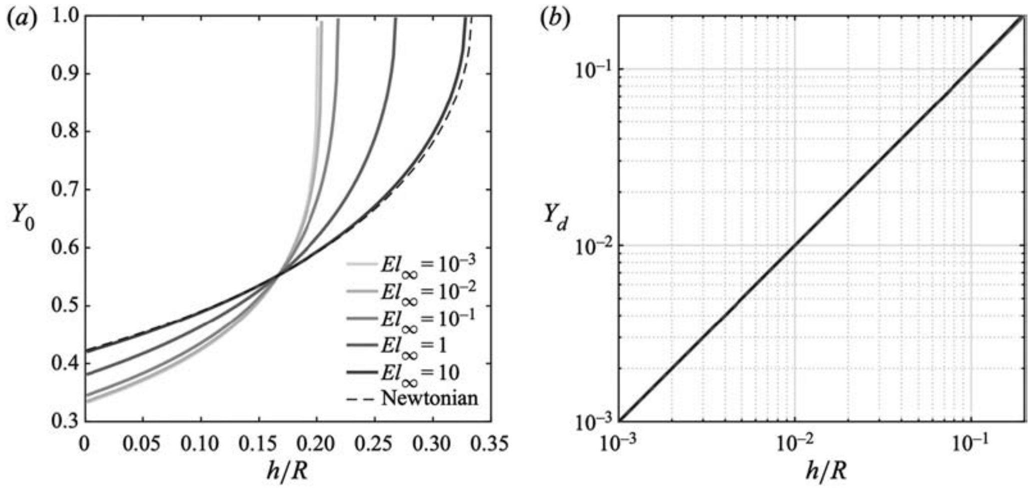

Fig. 9. Recirculation vortexes ahead of the Taylor bubble. (a) Location of the center of the recirculating vortices ahead of the bubble as a function of the Ellis number. (b) Location of the dividing streamline as a function of Ellis number. The picture has been taken from Picchi et al. [3] with permission from Cambridge University Press.

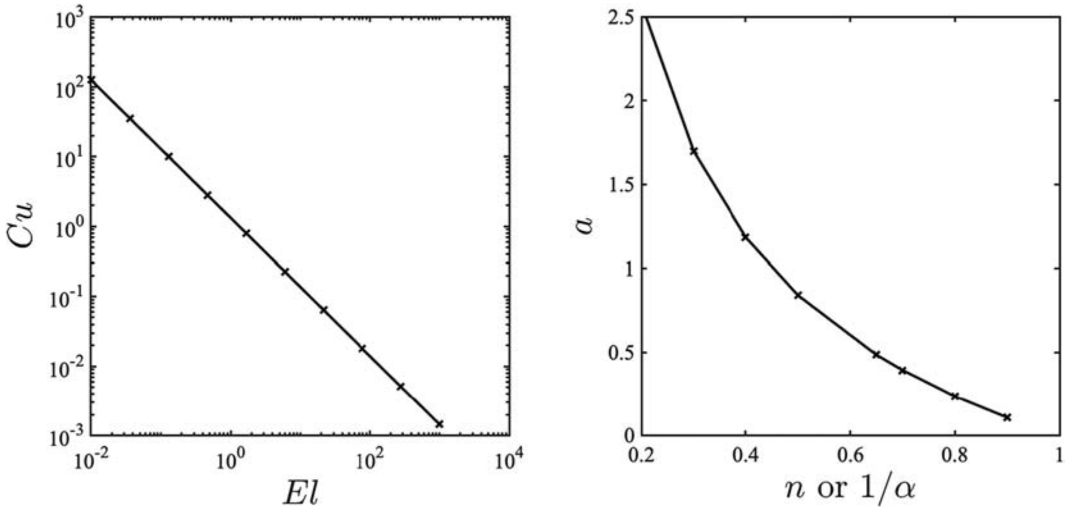

Fig. 10. Correspondence between the Ellis and the Carreau viscosity models.

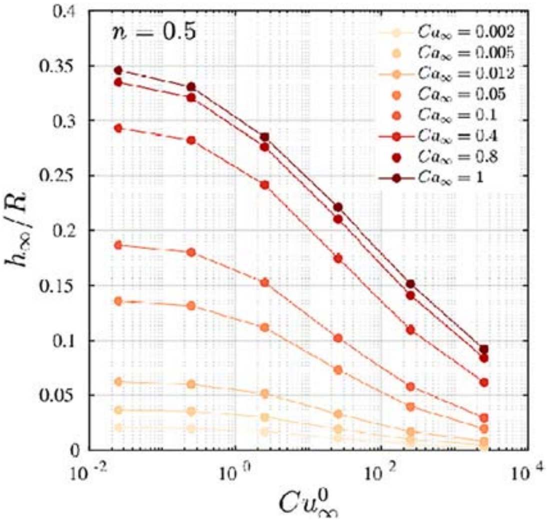

Fig. 11. Uniform film thickness as a function of the capillary and the Carreau numbers. The data are obtained from numerical simulations in a planar geometry.

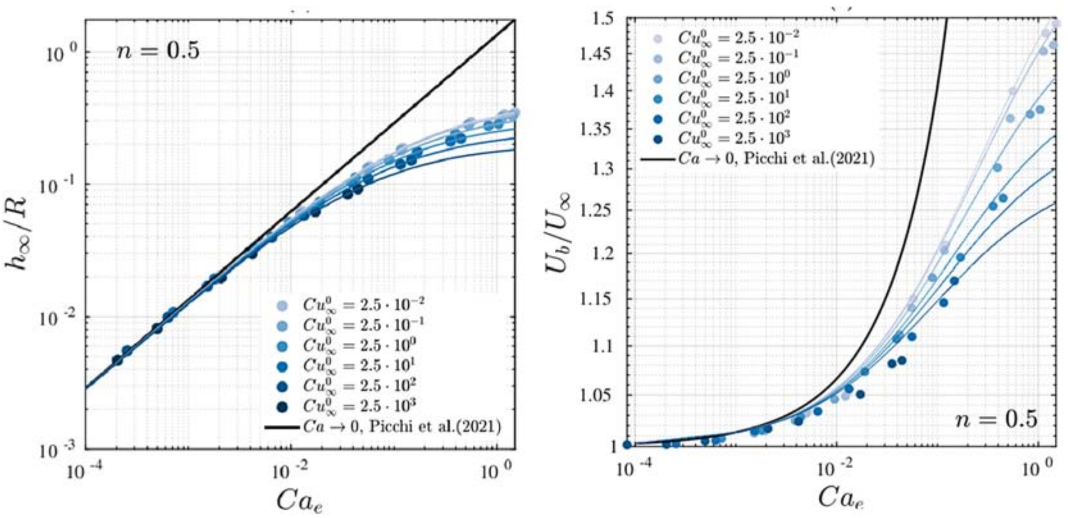

Fig. 12. Validation of the theoretical results with CFD data. (Left) Dimensionless film thickness as a function of the effective capillary number. (Right) Bubble speed ratio as a function of the effective capillary number. The lubrication theory by Picchi et al. [3] captures the evolution of both the film thickness and the bubble speed ratio in the small capillary number limit. An adaptation of the Aussillous and Quéré [4] correlation captures the behaviour up to finite capillary number for the case of shear-thinning fluids. Specifically, the functional dependence is preserved when the data are rescaled in terms of the effective capillary number.

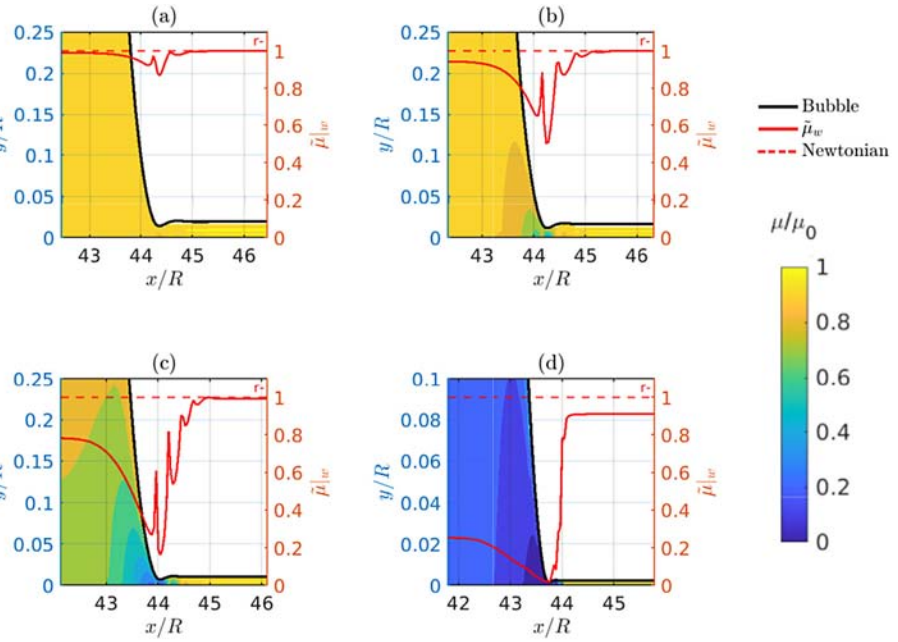

Fig. 13. Spatial distribution of the effective viscosity in the bubble rear. The cases depicted corresponds to the ones in Fig. 10. In all the cases the uniform film is the less-sheared region.

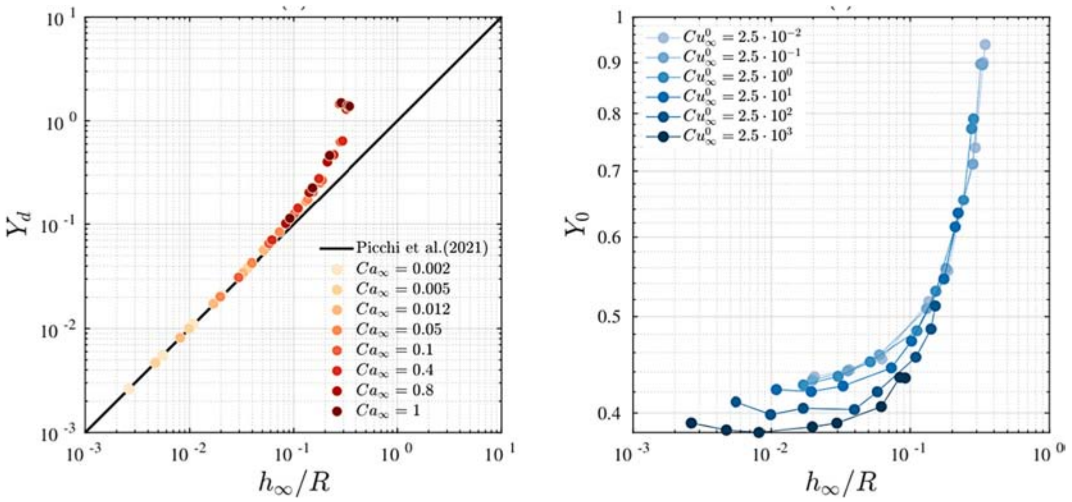

Fig. 14. Validation of the recirculation characteristics with CFD data. (Left) Location of the dividing streamline as a function of the capillary number; The prediction by Picchi et al. [3] capture the evolution in the limit of small capillary numbers. (Right) Heights of the center of the recirculating vortexes computed from the numerical simulations.

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CRediT authorship contribution statement

Davide Picchi: Writing – original draft, Formal analysis, Validation, Conceptualization, Methodology. **Andrea Aquino:** Writing – review & editing, Software. **Amos Ullmann:** Writing – review & editing, Supervision, Conceptualization. **Neima Brauner:** Writing – review & editing, Supervision, Conceptualization. **Pietro Poesio:** Writing – review & editing, Supervision, Conceptualization.

Data availability

No data was used for the research described in the article.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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