様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ６ 月 １５ 日現在

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研究課題名（和文）Modulation of turbulence by droplet coalescence

研究課題名（英文）Modulation of turbulence by droplet coalescence

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研究成果の概要（和文）：層流および乱流条件下における液滴合体現象の効果について数値計算を用いた研究に取り組んでいる．層流条件下においては，キャリア流体が非ニュートン流体である場合における，液滴のレオロジーが合体現象に与える影響を研究している．二相関の粘度比、シアシニングとシアシックニング、弾性への影響に着目して検討を行なっている．乱流条件下では，一様等方性乱流，一様剪断乱流およびチャネル流における合体現象の影響を研究している．前者の二つの条件下では粘度比と弾性の影響について研究を行なっており，後者においては合体を阻止することによって合体現象の役割を特定し、この効果を許容した場合の結果と比較した．

研究成果の学術的意義や社会的意義
We showed that droplets provide a spectral shortcut, subtracting energy from the large scales and re-introducing it at smaller scales, and coalescence changes the scale at which the energy is re-introduced. In wall-bounded flows, the effect of coalescence is stronger due to droplet migration.

研究成果の概要（英文）：The effect of coalescence on droplets suspensions has been investigate numerically in both laminar and turbulent flow conditions. In laminar flow conditions, I studied how the rheology of droplets is affected by coalescence when the carrier fluid is non-Newtonian. The effect of viscosity ratio among the two phases, shear-thinning and thickening, and elasticity have been tackled. In turbulent flow conditions, I studied the effect of coalescence in homogeneous isotropic turbulent flows, in homogeneous shear flows and in plane channel flows. In the first two, the effect of viscosity ratio and elasticity have been investigated, while in the latter the role of coalescence was singled out by preventing it and comparing the results to those from a case where this effect was allowed. In addition to the above analysis, I have worked on the numerical methods to simulate droplet laden system with different level of complexity, enabling the study of contact line dynamics and droplet evaporation.

研究分野：Fluid Dynamics

キーワード：Multiphase flows　Turbulence　Drops and bubbles

１．研究開始当初の背景

The scientific understanding of turbulent phenomena is a much discussed yet unsolved study topic, therefore turbulence is often referred to as classical physics' last unsolved problem (Frisch, Cambridge University Press, 1995). Since Richardson's work on the turbulent energy cascade (Richardson, Cambridge University Press, 1992), scientists have been fascinated by the multiscale nature of turbulent flows. When it comes to multiphase flows, which is the subject of this study, turbulent fluctuations can have a significant impact on the dynamics of the dispersed phase (Rosti et al, Physical Review Letters, 2018), which modulates turbulence in complex and sometimes unpredictable ways (Rosti et al, Physical Review Letters, 2018). (Rosti and Brandt, Physical Review Fluids, 2020). In this project, I focused on two-fluid systems in laminar and turbulent flows, where the resulting flows are affected both directly and indirectly by droplet feedback on the surrounding fluid. The ability of droplets to undergo topological changes through deforming, merging, and breaking up distinguishes droplet systems from other suspension flows. Two-phase flows have been the topic of various experimental (Takagi, Matsumoto, Annual Review of Fluid Mechanics, 2011; Besagni et al., Chemical Engineering, 2018) and computational studies in the past (Elghobashi, Annual Review of Fluid Mechanics, 2019; Rosti et al., Journal of Fluid Mechanics, 2019). Experimentally, the difficulty of differentiating various droplets has hampered comprehension, while numerically, the lack of proper numerical methods to cope with topological changes has limited understanding. Many features of this intricate interaction of the dispersed phase with the continuous phase, such as the influence of droplets and their coalescence on turbulent energy spectrum alterations, which is the subject of this study, are yet unknown.

２．研究の目的

My goal in this project was to figure out how finite-size droplets coalesce in laminar and turbulent flows. To do this, I explored flow configurations that are simple but universal, such as shear, channel, and triperiodic flows. The droplet dynamics were controlled by altering the system's coalescence efficiency in various ways, and the influence on the flow was evaluated by measuring common flow statistics and, when applicable, a scale-by-scale analysis in order to distinguish between the large-scale bulk dynamics of the two-phase system and the small-scale ones.

３．研究の方法

The problem at hand was tacked by means of direct numerical simulations. To study the multiphase systems, I used a recent version of the Volume of Fluid (VoF) method (Rosti et al. Acta Mechanica, 2019). The equations of motion are solved on a uniform staggered fixed Eulerian grid where the fluid velocity components are located on the cell faces and all other variables (density, viscosity, pressure, stress, and volume of fluid) at the cell centers. The time integration is performed with a fractional-step method based on the second-order Adams–Bashforth scheme. The indicator function H needed to capture the interface between the two fluids is found following the multidimensional tangent of hyperbola for interface capturing (MTHINC) method originally proposed by Ii et al. (Journal of Computational Physics, 2012) and transported with the volume of fluid method. The numerical code used has been extensively validated and used in the past. The code is written in FORTRAN90/95 and uses the MPI routines together with the 2DECOMP ones for parallel communications; the resulting numerical algorithm is highly efficient and strongly scalable, with an almost linear strong scaling is evident up to around 10000 cores for a problem with 1024^3 grid points. More details on the code, scaling tests and validations are reported online at http://groups.oist.jp/cffu/code. Furthermore, we also used the front-tracking method to make simulations of droplets, which cannot break up or coalesce.

４．研究成果

The effect of coalescence on droplets suspensions has been investigate numerically in both laminar and turbulent flow conditions. In laminar flow conditions, I studied how the rheology of droplets is affected by coalescence when the carrier fluid is non-Newtonian (Rosti and Takagi, Physics of Fluids, 2021). The effect of viscosity ratio among the two phases, shear-thinning and thickening, and elasticity have been tackled. In turbulent flow conditions, I studied the effect of coalescence in homogeneous isotropic turbulent flows (Crialesi-Esposito et al., Journal of Fluid Mechanics, 2022), in homogeneous shear flows (Scapin et al, Journal of Fluid Mechanics, 2022) and in plane channel flows (Cannon et al., Physics of Fluids, 2021). In addition to the above analysis, I have worked on the numerical methods to simulate droplet laden system with different level of complexity, enabling the study of contact line dynamics (Shahmardi et al., Journal of Computational Physics, 2021) and droplet evaporation (Della Barba et al., Computer and Fluids, 2021). Below I will focus on two main results discussed in Crialesi-Esposito et al. (Journal of Fluid Mechanics, 2022) and in Cannon et al. (Physics of Fluids, 2021).

We investigate emulsions in fairly high Reynolds number homogeneous and isotropic turbulence (HIT). Direct numerical simulations are utilized to solve the problem, with the volume of fluid being employed to simulate the complicated aspects of the liquid–liquid interface. The volume fraction, viscosity ratio, and large-scale Weber number of a combination of two iso-density fluids are altered with the purpose of understanding their function in turbulence modulation. We discovered that energy reduces at large scales and increases at small scales, as shown in Figure 1. Furthermore, the Hinze scale is found to describe the pivoting point of the energy spectra with a good approximation. The dispersed phase modifies the classical mechanics of energy transport in the following ways: i) the energy transfer by nonlinear advection terms decreases as the surface tension force absorbs energy at large scales; ii) the surface tension force also transfers energy to small scales, well within the dissipative range of the corresponding single-phase flow, forcing viscous dissipation to be active at even smaller scales. By studying the droplet size distributions, we found both the 10/3 and 3/2 scalings, implying that the dimensional considerations that led to their formulation are proven in HIT settings.

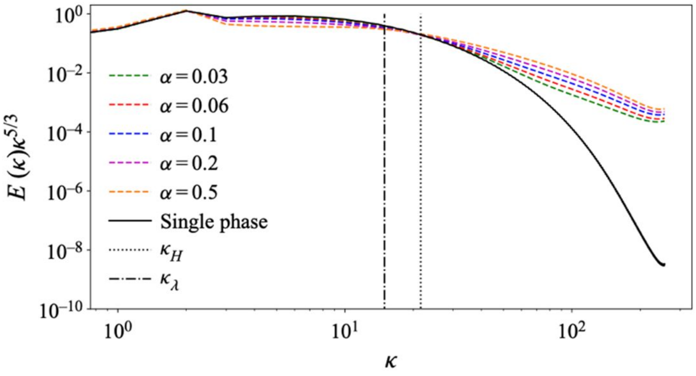

Figure 1: Energy spectra for various volume fractions of the dispersed phase.

Next, the influence of droplet coalescence on turbulent wall-bounded flows was investigated using direct numerical simulations. To model turbulent channel flows containing coalescing and non-coalescing droplets, the volume-of-fluid and front-tracking methods are utilized, respectively. We discovered that coalescing droplets have roughly no effect on drag, whereas non-coalescing droplets steadily increase drag as the volume fraction of the dispersed phase increases: at 10% volume fraction, non-coalescing droplets have a 30% increase in drag, whereas coalescing droplets have less than a 4% increase. We show by looking at the wall-normal placement of droplets in the channel that non-coalescing droplets enter the viscous sublayer, causing an interfacial shear stress, which reduces the budget for viscous stress in the channel. Coalescing droplets, on the other hand, migrate into the channel's bulk, generating huge aggregates that have no effect on the viscous shear stress while dampening the Reynolds shear stress. We show this by connecting the centerline velocity to the mean viscous shear stress integrated in the wall-normal direction.

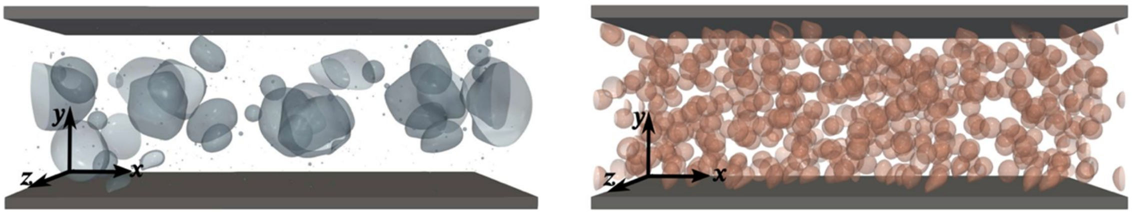

Figure 2: Snapshot of coalescing and non-coalescing droplets.

The above studies showed that droplet coalescence has a general tendency of reducing the effective viscosity of the system, as well as reducing the backreaction of the flow, which results less disturbed by the presence of the dispersed phase. The scale-by-scale analysis showed that droplets provide a spectral shortcut, subtracting energy from the large scales and re-introducing it at smaller scales. Coalescence changes the scale of the droplets and thus the scale at which the energy is re-introduced in the system. In the case of wall-bounded flows, the effect of coalescence is even more pronounced, due to the additional migration effects that are more pronounced when coalescence is allowed.

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　0件／うち国際共著　5件／うちオープンアクセス　0件）

１．著者名 Shahmardi Armin、Rosti Marco Edoardo、Tammisola Outi、Brandt Luca	４．巻 443
２．論文標題 A fully Eulerian hybrid immersed boundary-phase field model for contact line dynamics on complex geometries	５．発行年 2021年
３．雑誌名 Journal of Computational Physics	６．最初と最後の頁 110468～110468
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jcp.2021.110468	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Cannon Ianto、Izbassarov Daulet、Tammisola Outi、Brandt Luca、Rosti Marco E.	４．巻 33
２．論文標題 The effect of droplet coalescence on drag in turbulent channel flows	５．発行年 2021年
３．雑誌名 Physics of Fluids	６．最初と最後の頁 085112～085112
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0058632	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Rosti Marco E.、Takagi Shu	４．巻 33
２．論文標題 Shear-thinning and shear-thickening emulsions in shear flows	５．発行年 2021年
３．雑誌名 Physics of Fluids	６．最初と最後の頁 083319～083319
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0063180	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Scapin Nicolo、Dalla Barba Federico、Lupo Giandomenico、Rosti Marco Edoardo、Duwig Christophe、Brandt Luca	４．巻 934
２．論文標題 Finite-size evaporating droplets in weakly compressible homogeneous shear turbulence	５．発行年 2022年
３．雑誌名 Journal of Fluid Mechanics	６．最初と最後の頁 A15
掲載論文のDOI（デジタルオブジェクト識別子） 10.1017/jfm.2021.1140	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Crialesi-Esposito Marco、Rosti Marco Edoardo、Chibbaro Sergio、Brandt Luca	4．巻 940
2．論文標題 Modulation of homogeneous and isotropic turbulence in emulsions	5．発行年 2022年
3．雑誌名 Journal of Fluid Mechanics	6．最初と最後の頁 19
掲載論文のDOI（デジタルオブジェクト識別子） 10.1017/jfm.2022.179	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計8件（うち招待講演　2件／うち国際学会　2件）

1．発表者名 Ianto Cannon; Marco E. Rosti
2．発表標題 Droplet coalescence in turbulent channel flows
3．学会等名 34th Computational Fluid Dynamics Symposium of Japan Society of Fluid Mechanics
4．発表年 2020年

1．発表者名 M. Abdelgawad; Marco E. Rosti
2．発表標題 Single droplet deformation in Couette flow
3．学会等名 34th Computational Fluid Dynamics Symposium of Japan Society of Fluid Mechanics
4．発表年 2020年

1．発表者名 Marco E. Rosti
2．発表標題 Droplets in shear flows
3．学会等名 BICTAM-CISM Symposium on Dispersed Multiphase Flows（招待講演）
4．発表年 2021年

１．発表者名
Ianto Cannon; Marco E. Rosti

２．発表標題
Coalescence reduces drag in turbulent bubbly channel flows

３．学会等名
EUROMECH Colloquium 621 - Transport and fluxes in dispersed turbulent flow

４．発表年
2021年

１．発表者名
Marco E. Rosti

２．発表標題
Droplets in shear flows

３．学会等名
ICTAM 2020+1

４．発表年
2021年

１．発表者名
Ianto Cannon; Marco E. Rosti

２．発表標題
Coalescence and drag in bubbly channel flows

３．学会等名
Annual Meeting of the Japanese Society of Fluid Mechanics

４．発表年
2021年

１．発表者名
Ianto Cannon; Marco E. Rosti

２．発表標題
Direct numerical simulations of surfactants in bubbly tri-periodic turbulent flows

３．学会等名
APS DFD meeting（国際学会）

４．発表年
2021年

１．発表者名 M. Abdelgawad; Marco E. Rosti
２．発表標題 Droplet breakup limits in simple shear flows
３．学会等名 ESCHM-ISCH-ISB 2021, Fukuoka（招待講演）（国際学会）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関