

Heat transfer and mixing in turbulent water-in-oil and oil-in-water emulsions

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We numerically investigate turbulent heat transfer in water-in-oil (W/O) and oil-in-water (O/W) emulsions using direct numerical simulations coupled with a phase-field method. Heat is treated as a passive scalar, initially confined within the dispersed phase and subsequently transferred to the carrier fluid. The two emulsions share identical density and thermal diffusivity, while the oil phase is four times more viscous than water. To isolate convective effects, the same Péclet number ($Pe = 2400$) is imposed in both configurations. Viscosity contrast strongly affects local flow and scalar dynamics, producing enhanced velocity fluctuations and mixing in the water phase and reduced activity in the oil phase. Reversing the dispersed and carrier phases redistributes these local mixing mechanisms between the drop interior and the surrounding fluid. This redistribution leads to similar global heat-transfer rates and comparable thermal transient in both emulsions, despite fundamentally different phase-conditioned flow and mixing dynamics.

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I. INTRODUCTION

Oil-water emulsions play a central role in a wide range of industrial applications, from chemical reactors to food preparation and pharmaceutical products. Within the broad field of multiphase flow systems, oil-water emulsions represent a canonical model problem, as the two liquids typically share similar density and thermal diffusivity but may differ significantly in viscosity. A distinctive property of oil-water emulsions is their metastable nature, which allows them to undergo phase inversion, whereby the dispersed phase becomes continuous and vice versa [1–3]. Reversing the roles of oil and water between dispersed and carrier phases alters the relative importance of diffusive contributions—either within the droplets or in the surrounding fluid—thus leading to modifications of the local turbulence structures and of the corresponding transport mechanisms.

In many applications, emulsion preparation requires specific temperatures or the addition of chemical species, such as surfactants, to facilitate the process [4–7]. The corresponding heat and mass transfer phenomena in these complex systems remain, however, poorly understood. While scalar mixing in canonical single-phase turbulent flows has been the subject of many fundamental investigations and is now relatively well characterized [8–13], extending this understanding to emulsions is more challenging. This difficulty arises from the presence of deformable interfaces and phase-dependent transport mechanisms, which introduce additional layers of complexity [14–20]. In addition, breakage and coalescence events can influence mixing by either merging flow regions

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that were previously separated or, conversely, separating regions that were previously connected [21–23]. The mixing of a scalar in turbulence is often studied through the evolution of a scalar initially confined to a localized region (or blob), which subsequently mixes with the surrounding fluid until equilibrium is reached [24,25]. An analogous problem arises in multiphase flows when the scalar is initially confined to one of the two phases. The central questions then concern the time required to achieve complete mixing and the temporal evolution of this process, including the associated scaling laws. In general, the rate of mixing depends on both diffusive and convective mechanisms and on their relative importance. In multiphase flows, this balance may differ between phases owing to contrasts in thermophysical properties and interfacial effects [26–28]. Likewise, turbulence characteristics and the resulting flow topology can differ markedly between the continuous carrier phase and the dispersed phase [17,19,29–34].

Motivated by these considerations, we investigate the role of the viscosity ratio on scalar mixing by performing phase-field-based direct numerical simulations of the mixing of a passive scalar (temperature) in water-in-oil and oil-in-water emulsions. The two systems considered correspond to opposite configurations—water dispersed in oil and oil dispersed in water—differing only in which fluid constitutes the continuous and dispersed phases. Buoyancy effects and phase-change phenomena are neglected to isolate viscosity-driven mechanisms, and temperature is therefore treated as a passive scalar, initially confined within the dispersed phase. The adopted setup mimics the injection of a warm dispersed liquid phase into a colder turbulent continuous phase, under a small temperature difference, as commonly encountered in chemical processing, emulsification systems, and thermal mixing devices. The two configurations are designed to share the same Péclet number, density, and thermal diffusivity, while differing only in viscosity contrast and phase occupancy. This choice isolates viscosity-induced modifications of turbulence and convection by maintaining equal diffusive importance in oil and water, allowing the impact of viscosity contrast to be examined. The resulting local and global mixing behavior is then analyzed to reveal how phase interchange redistributes turbulent transport pathways. The paper is organized as follows. Sections II and III describe the governing equations and the simulation setup. Section IV presents the results obtained, focusing on the global heat transfer behavior and on the local flow and temperature fields modifications induced by viscosity. Finally, we draw our conclusions in Sec. V.

II. GOVERNING EQUATIONS

We consider the flow of oil-water turbulent emulsions in a channel flow configuration. The dispersed phase behavior is described using a phase-field method [35–38], which relies on the introduction of a scalar variable, the phase field ϕ . This variable has a uniform value in the bulk of each phase ($\phi = +1$ inside the drops; $\phi = -1$ inside the carrier fluid) and undergoes a smooth transition across a thin interfacial layer that separates the two phases. The characteristic length scale of this layer is determined by the Cahn number $\text{Ch} = \xi/h$, the ratio between its dimensional value and the channel half-height h . The transport of the phase-field variable is described by the Cahn-Hilliard equation, which in dimensionless form reads as

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \frac{1}{\text{Pe}_\phi} \nabla^2 \mu_\phi + f_p, \quad (1)$$

where $\mathbf{u} = (u, v, w)$ is the velocity vector. The first term on the right-hand side represents the flux induced by the phase-field chemical potential

$$\mu_\phi = \frac{\delta \mathcal{F}}{\delta \phi} = \phi^3 - \phi - \text{Ch}^2 \nabla^2 \phi, \quad (2)$$

which is obtained from a Ginzburg-Landau free-energy functional. The second term on the right-hand side, f_p , represents a regularization contribution that is employed to better preserve the hyperbolic tangent profile of the transition layer during the computation [39,40]. The phase-field Péclet number, $\text{Pe}_\phi = u_\tau h / (\mathcal{M}_\phi \beta)$, represents the ratio of diffusive to convective timescales, where

u_τ is the friction velocity, $\mathcal{M}_\phi$ is the phase-field mobility, and β is a positive constant used in the dimensionless procedure [41].

To describe the hydrodynamics of the multiphase system, the Cahn-Hilliard equation is coupled with the Navier-Stokes equations. The presence of a deformable interface (and of the corresponding surface tension forces) is accounted for by introducing an interfacial term in the Navier-Stokes equations. We consider two fluids with the same density ($\rho_c = \rho_d = \rho$) but different viscosity ($\mu_c \neq \mu_d$). With this assumption, continuity and Navier-Stokes equations in dimensionless form read as

$$\nabla \cdot \mathbf{u} = 0, \quad (3)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{\text{Re}_\tau} \nabla \cdot [\mu(\phi)(\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \frac{3}{\sqrt{8}} \frac{\text{Ch}}{\text{We}} \nabla \cdot \mathbf{T}_c, \quad (4)$$

where p is the pressure field, $\mu(\phi)$ is the viscosity map, and $\mathbf{T}_c$ is the Korteweg tensor. The viscosity map is computed from the phase-field variable using a linear interpolation [42], namely as

$$\mu(\phi) = 1 + (\mu_r - 1) \frac{\phi + 1}{2}, \quad (5)$$

where $\mu_r = \mu_d/\mu_c$ is the dispersed-to-carrier viscosity ratio. The Korteweg tensor, used to account for the surface tension forces, is defined as

$$\mathbf{T}_c = |\nabla \phi|^2 \mathbf{I} - \nabla \phi \otimes \nabla \phi, \quad (6)$$

where $\mathbf{I}$ is the identity matrix. This approach is based on the continuum surface stress formulation [43,44] applied in the context of the phase-field method, and is analytically equivalent to the chemical potential forcing [45]. The dimensionless groups appearing in the Navier-Stokes equations are the shear Reynolds number Re_τ (ratio between inertial and viscous forces), and the Weber number We (ratio between inertial and surface tension forces), which are defined as

$$\text{Re}_\tau = \frac{\rho u_\tau h}{\mu_c}, \quad \text{We} = \frac{\rho u_\tau^2 h}{\sigma}, \quad (7)$$

where σ is the surface tension value and the Reynolds number is defined using the viscosity of the carrier fluid as a reference [42,46].

To describe the temperature field, the energy equation is solved. We consider two fluids with the same thermal conductivity λ and specific heat capacity C_p . As a consequence, also the thermal diffusivity, $\alpha = \lambda/\rho C_p$, is the same. Within these assumptions, the energy equation can be written in dimensionless form as

$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \frac{1}{\text{Re}_\tau \text{Pr}_c} \nabla^2 \theta, \quad (8)$$

and matches the transport equation of a passive scalar. In the expression above θ is the temperature and Pr_c is the carrier phase Prandtl number, defined as

$$\text{Pr}_c = \frac{\nu_c}{\alpha}, \quad (9)$$

where $\nu_c = \mu_c/\rho$ is the kinematic viscosity (momentum diffusivity) of the carrier phase. From a physical viewpoint, the Prandtl number represents the momentum-to-thermal diffusivity ratio. The dispersed phase Prandtl number, Pr_d , can be computed as $\text{Pr}_d = \mu_r \text{Pr}_c$.

III. SIMULATION SETUP

We consider the flow of oil-water emulsions in an adiabatic closed channel configuration driven by an imposed constant pressure gradient. The computational domain has dimensions $L_x \times L_y \times L_z = 4\pi h \times 2\pi h \times 2h$. The Weber number is kept constant at $\text{We} = 3.0$, corresponding to a surface tension representative of liquid-liquid systems [47]. Two configurations are

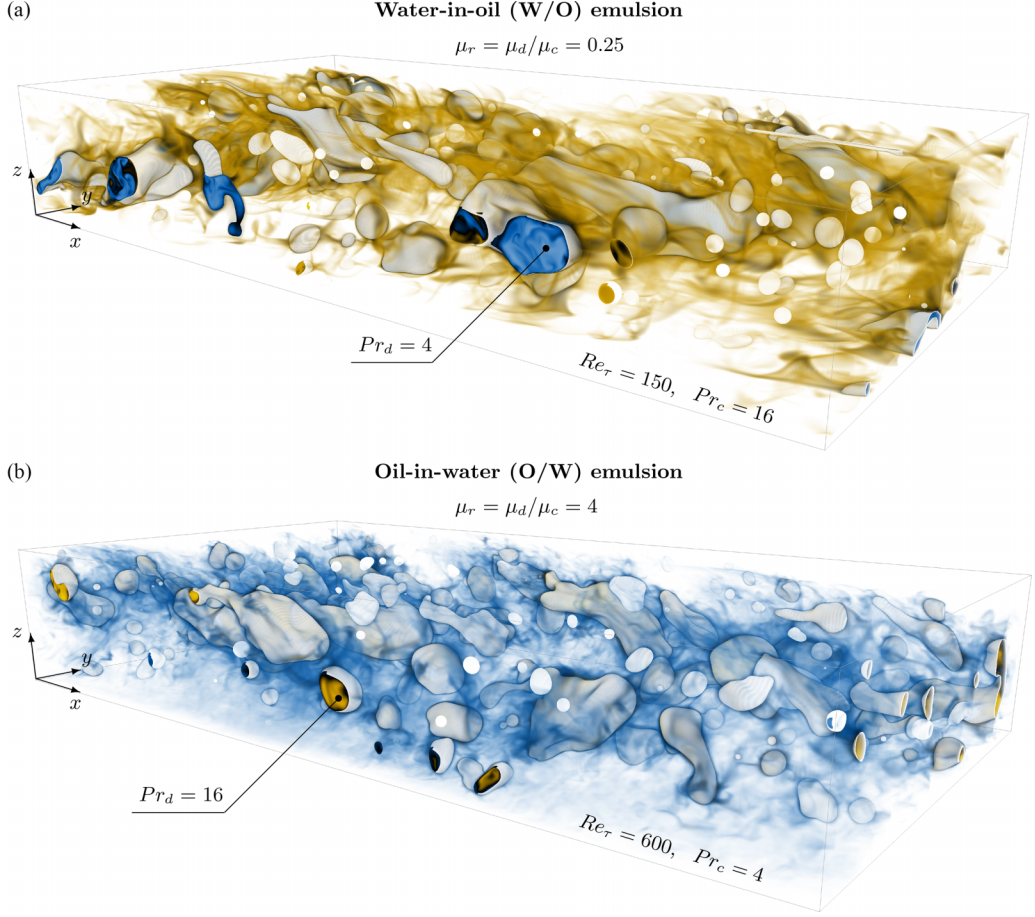


FIG. 1. Qualitative visualization of water-in-oil (W/O) emulsion (a), where water drops are dispersed in an oil carrier phase, and of oil-in-water (O/W) emulsion (b), where oil drops are dispersed in a water carrier phase. The temperature field is volume-rendered with a yellow-blue and blue-yellow colormaps for the W/O and O/W emulsions, respectively. The drops surface, identified as the isolevel $\phi = 0$, is shown in white.

investigated: a water-in-oil (W/O) emulsion and an oil-in-water (O/W) emulsion, illustrated in Figs. 1(a) and 1(b), respectively. The oil considered is four times more viscous than water, while the remaining thermophysical properties are the same for both oil and water (density, thermal diffusivity). The same Péclet number is imposed for all cases, namely $Pe = 2400$. For the W/O emulsion [Fig. 1(a)], the shear Reynolds number is set to $Re_\tau = 150$, and the corresponding drop-to-carrier viscosity ratio is $\mu_r = 1/4$. The Prandtl number of the oil carrier phase is set equal to $Pr_c = 16$, yielding a dispersed-phase Prandtl number $Pr_d = \mu_r Pr_c = 4$. For the O/W emulsion [Fig. 1(b)], a shear Reynolds number of $Re_\tau = 600$ is considered, with a drop-to-carrier viscosity ratio $\mu_r = 4$. The Prandtl number of the water carrier phase is $Pr_c = 4$ while the dispersed-phase Prandtl number is $Pr_d = \mu_r Pr_c = 16$. In addition to these two cases, a reference matched-viscosity configuration at $Re_\tau = 300$ is investigated, for which $Pr_c = Pr_d = 8$. Three single-phase flow simulations at $Re_\tau = 150, 300$, and 600 are also performed as a reference. The governing equations are solved using a pseudospectral method, employing the GPU-accelerated open-source solver FLOW36 [48]. To reduce the computational cost, a dual-grid strategy is adopted [48,49]. The continuity, Navier-Stokes, and Cahn-Hilliard equations are solved on a grid with resolution

TABLE I. Overview of simulation parameters.

Case	Re_τ	Pr_c	μ_r	Pr_d	We	$N_x \times N_y \times N_z$ (NS + CH)	$N_x \times N_y \times N_z$ (Scalar)
Water-in-oil (W/O) emulsion	150	16	0.25	4	3.0	$1024 \times 512 \times 1025$	$2048 \times 1024 \times 1025$
Reference (Ref) emulsion	300	8	1.00	8	3.0	$1024 \times 512 \times 1025$	$2048 \times 1024 \times 1025$
Oil-in-water (O/W) emulsion	600	4	4.00	16	3.0	$1024 \times 512 \times 1025$	$2048 \times 1024 \times 1025$
Single-phase (SP)	150					$1024 \times 512 \times 1025$	
Single-phase (SP)	300					$1024 \times 512 \times 1025$	
Single-phase (SP)	600					$1024 \times 512 \times 1025$	

$N_x \times N_y \times N_z = 1024 \times 512 \times 1025$, whereas the energy equation, which exhibits finer-scale structures, is solved on a refined grid with resolution $N_x \times N_y \times N_z = 2048 \times 1024 \times 1025$. The selected grid resolution is sufficient to properly resolve all flow and temperature scales, including those within the dispersed phase, where a Reynolds number is estimated as $\sim Re_\tau / \mu_r$, using the same characteristic length and velocity scale adopted for the carrier fluid. This estimate is intentionally conservative, since the drop size is expected to be at most comparable to the half-channel height, while the characteristic velocity of the internal flow is likely comparable to or smaller than the friction velocity. A summary of the simulation parameters is provided in Table I. In addition, an overview of the grid spacing relative to the Kolmogorov and Batchelor scales is reported in Table II. Based on the chosen grid, the Cahn number is set to $Ch = 0.01$, and the phase-field Péclet number is imposed according to the scaling $Pe_\phi = 1/Ch = 100$, ensuring convergence to the sharp-interface limit [49,50].

The emulsion simulations are initialized with a regular array of 256 spherical drops of diameter $0.4h$, injected in a fully developed turbulent flow field. The resulting dispersed-phase volume fraction is $\Phi = V_d / (V_c + V_d) = 5.4\%$, where V_d and V_c denote the volumes of the drops and the carrier fluid, respectively. The temperature field is initialized such that the scalar is confined within the drops. This setup corresponds to initially warm droplets, with temperature $\theta_{d,0} = 1$, dispersed in an initially cold carrier fluid, with temperature $\theta_{c,0} = -1$. To avoid numerical instabilities associated with a discontinuous temperature field in spectral methods, the transition between the drops and the carrier fluid is initially smoothed using a hyperbolic tangent kernel.

IV. RESULTS

The results of the numerical simulations are now presented. First, the heat transfer process is described from a global perspective. Then, we detail the modifications induced by viscosity on the interfacial behavior, flow field and temperature statistics in the two phases. In the following, oil phase quantities are shown in yellow, water phase quantities in blue, and reference results in gray, while quantities for the entire two-phase system are illustrated in black. All quantities are reported in outer units.

TABLE II. Grid spacing of the flow and temperature fields, together with the Kolmogorov and Batchelor scales at the channel center in outer units, conditioned in the carrier and dispersed phase, for the W/O, Ref, and O/W cases.

Case	Re_τ	Pr_c	Pr_d	Δx	Δy	Δz	η_{k_c}	η_{k_d}	Δx_θ	Δy_θ	Δz_θ	η_{θ_c}	η_{θ_d}
W/O	150	16	4	0.0123	0.0123	0.0031	0.0236	0.0089	0.0061	0.0061	0.0031	0.0059	0.0045
Ref	300	8	8	0.0123	0.0123	0.0031	0.0139	0.0139	0.0061	0.0061	0.0031	0.0049	0.0057
O/W	600	4	16	0.0123	0.0123	0.0031	0.0081	0.0228	0.0061	0.0061	0.0031	0.0040	0.0057

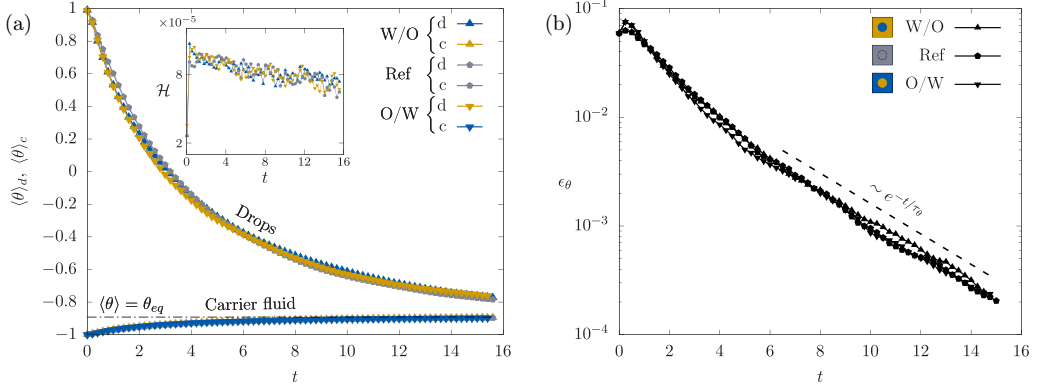


FIG. 2. Time evolution of phase-conditioned mean temperature (a), heat transfer coefficient [panel (a), inset] and thermal energy dissipation rate (b), for the different cases. The water, the reference and the oil phase are reported with blue, gray and yellow colors, respectively, for both drops and carrier fluid; the black color refers to the entire two-phase system (inset: blue for W/O, gray for Ref, yellow for O/W). The W/O, Ref and O/W cases are marked with upward triangles, pentagons and downward triangles symbols, respectively. The subscripts d and c identify the drops and carrier fluid contributions. The equilibrium temperature of the system, θ_{eq} , is shown with a horizontal dash-dotted line, while the exponential decay of the dissipation rate is indicated by a dashed line. The exponential decay is characterized by a diffusive timescale $\tau_\theta \simeq 2.73$.

A. Global heat transfer behavior

We start by analyzing the heat transfer process over time from a global point of view. Figure 2(a) shows the evolution of the mean temperature of the two phases (denoted by angular brackets), which has been computed using the phase field to distinguish between carrier and dispersed phases. The W/O emulsion, reference and O/W emulsion cases are shown with upward triangles, pentagons and downward triangles, respectively. Colors (yellow for oil, blue for water, and gray for the reference case) are used to identify the different phases. All cases evolve asymptotically toward thermodynamic equilibrium: the mean temperature of the drops decreases while the mean temperature of the carrier phase slightly increases. From energy conservation, the thermodynamic equilibrium—under adiabatic wall conditions—depends only on the volume fraction and the initial temperatures of the two phases,

$$\theta_{eq} = \theta_{c,0}(1 - \Phi) + \theta_{d,0}\Phi, \quad (10)$$

where $\theta_{d,0}$ and $\theta_{c,0}$ are the initial drops and carrier fluid temperature, and Φ is the volume fraction. The three cases converge to the equilibrium condition at a similar rate. This observation is confirmed by the time evolution of the heat transfer coefficient, inset of Fig. 2(a). The heat transfer coefficient has been computed as [22,51]

$$\mathcal{H} = \frac{(\langle \theta \rangle_d^{n+1} - \langle \theta \rangle_d^n)}{A \Delta t (\langle \theta \rangle_d^{n+1/2} - \langle \theta \rangle_c^{n+1/2})}, \quad (11)$$

where n and $n + 1$ represent two subsequent time steps, $n + 1/2$ identifies a quantity evaluated halfway between the steps n and $n + 1$, A is the interfacial area and Δt is the time step between two snapshots. After an initial increase, the heat transfer coefficient decreases monotonically on average, with superimposed oscillations.

This trend and the obtained values are similar for all cases, thus confirming that the global behavior of the system is also similar.

The global heat transfer behavior can be also analyzed using the budget equation for the temperature variance based on the global temperature fluctuation, $\theta' = \theta - \langle \theta \rangle$, where $\langle \theta \rangle$ is the

average temperature of the system, which corresponds to the equilibrium temperature θ_{eq} . As the walls are adiabatic and impermeable, the budget equation for the temperature reduces to [52]

$$\frac{\partial \langle \theta'^2 \rangle}{\partial t} = -\epsilon_\theta, \quad (12)$$

where ϵ_θ is the thermal energy dissipation rate, which is defined as follows:

$$\epsilon_\theta = \frac{2}{\text{Pe}} \langle |\nabla \theta'|^2 \rangle. \quad (13)$$

From a physical point of view, the equation above shows that the temperature fluctuations are reduced by dissipative mechanisms as time evolves, until a complete mixing is achieved. Thanks to the direct link between temperature variance and the dissipation rate, the latter one can be used as an indicator of the mixing rate attained in the system [52]. Figure 2(b) shows the time evolution of the thermal dissipation rate. We notice that the scalar dissipation rate decays in a similar manner for all cases. The decay is initially more pronounced and gradually weakens at later times ($t > 5$). In this late-time regime, scalar dissipation exhibits an approximately exponential decay, suggesting that its evolution can be interpreted as a first-order diffusive relaxation process. The corresponding diffusive timescale, defined as the inverse of the decay rate, can be expressed in dimensional form as $\tau_\theta = l_d^2/\alpha$, where l_d denotes the characteristic length scale of the scalar gradients. In dimensionless form, this timescale becomes $\tau_\theta = l_d^2 \text{Pe}$. From the measured decay rate ($\tau_\theta \simeq 2.73$), we infer a characteristic length scale $l_d \simeq 7 \eta_\theta$, where η_θ is the Batchelor length scale computed in the carrier phase, which takes similar values in all cases owing to the identical Péclet number. The observed decay time, being several times larger than the Batchelor time, suggests that scalar dissipation is not governed by the smallest instantaneous scalar gradients, but rather by larger-scale residual scalar structures and interfacial geometry, which limit the efficiency of molecular diffusion.

B. Local effects on interface, flow, and temperature field

The global results suggest that heat transfer is robust to the interchange of dispersed and carrier phases. This behavior may be attributed to one of the following explanations. On the one hand, the effect of the viscosity ratio on heat transfer may be negligible. On the other hand, viscosity-induced effects in the W/O and O/W systems may act in opposite directions and thus balance out at macroscopic level. To identify the relevant mechanism and, in particular, to assess whether a nonunitary viscosity ratio induces any measurable modifications in the W/O and O/W emulsions, we examine the temperature, phase, and velocity fields from a local perspective. The possible pathways through which viscosity modifies heat transfer are graphically summarized in Fig. 3. Starting from the left side, variations in viscosity affect the velocity field by modifying viscous dissipation, which subsequently impacts both the temperature field (upper arrow) and phase field (central downward arrow) through convective transport. The latter mechanism also acts in the opposite direction: the phase field, governed by the Cahn-Hilliard equation, feeds back into the momentum equation via surface tension forces as well as modifying the viscosity map (bottom left arrow). In particular, the viscosity ratio between the drops and the carrier fluid influences the dynamics of the drops. Indeed, increasing droplet viscosity damps internal turbulent fluctuations and reduces deformability, thereby lowering the frequency of breakage and coalescence events [42,46]. Conversely, a lower droplet viscosity intensifies internal flow activity and amplifies external forcing, leading to higher deformability and increased interfacial activity. Eventually, these dynamics modulate the heat transfer process by changing the total interfacial area available for heat exchange through the continuous deformation, elongation, and breakage of the drops.

1. Characterization of the dispersed phase

While thermal mixing occurs within the bulk of both the dispersed and carrier phases, heat exchange between them takes place at the oil-water interface. In turbulent conditions, this interface

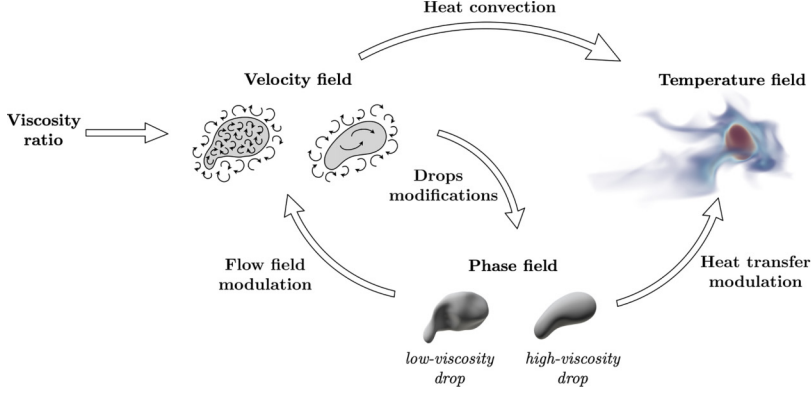


FIG. 3. Pathways of viscosity-induced modifications in the velocity, phase, and temperature fields. Starting from the left, viscosity contrasts induce changes in the flow field, which alter the dispersed-phase topology; in turn, phase-field changes feed back onto the flow. These coupled modifications of flow and phase dynamics subsequently affect heat transfer by changing the relative importance of convection and the available interfacial area.

evolves continuously in time. Consequently, variations in the total interfacial area can significantly influence the amount of heat transferred from the dispersed to the carrier phase. These variations originate from both morphological changes, associated with drop deformation, and topological changes, driven by breakage and coalescence events. To elucidate the role played by interface dynamics in determining the observed global thermal behavior, we compare the W/O, reference, and O/W systems in terms of their drop size distributions (DSD) and interfacial area evolution.

To evaluate the attainment of a steady-state configuration, the time evolution of the interfacial area, shown in the inset of Fig. 4 (normalized by the initial interfacial area A_0), is monitored [32]. The area is computed by integrating the volume of a thin interfacial layer, defined based on appropriate phase-field values, and dividing it by its thickness. This approximation is reasonably accurate provided the chosen interfacial layer is sufficiently thin. In all cases, the interfacial area undergoes a substantial initial decrease over the range $0 < t < 5$, after which it evolves with only small oscillations around an approximately steady value. The steady-state levels differ slightly between cases, although no clear or systematic trend can be identified. Since the most significant variations occur for $t < 5$ and only minor changes appear afterwards, we regard the window $t > 5$ as steady-state from the standpoint of drop dynamics, and heat transfer statistics are likewise averaged within this range. The robustness of this choice was verified through additional analysis confirming that, beyond $t = 5$, the observables exhibit no significant variation across different time windows. For brevity, we therefore refer to the interval $5 < t < 16$ as the steady-state in the remainder of the manuscript.

Figure 4 shows the DSDs obtained at steady-state for the cases considered (W/O, upward blue triangles; Ref, gray pentagons; O/W, yellow downward triangles). To compute the DSD, the equivalent sphere diameter for each drop is considered,

$$d_{eq,i} = \left(\frac{6V_i}{\pi} \right)^{1/3}, \quad (14)$$

where V_i is the volume of the i th droplet. The Kolmogorov-Hinze scale, used to distinguish between the coalescence and breakage regimes according to the Kolmogorov-Hinze framework [59,60], has been computed as

$$d_H = 0.725 \left(\frac{We}{Re_\tau} \right)^{-3/5} |\epsilon|^{-2/5}, \quad (15)$$

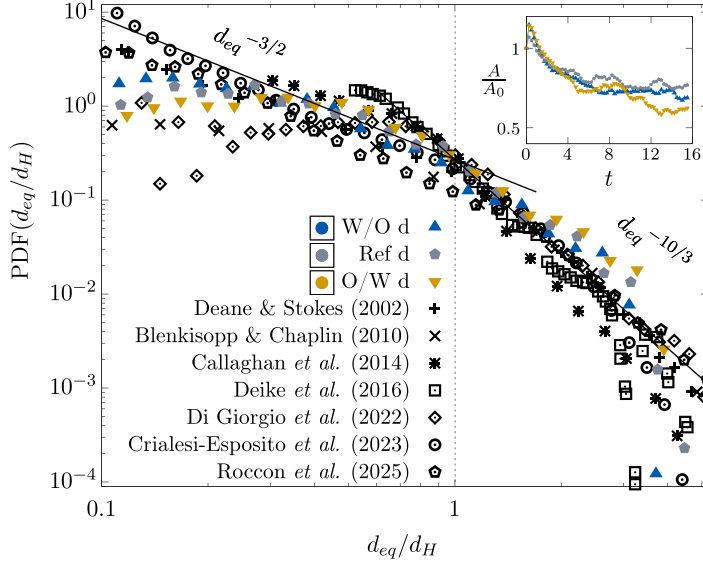


FIG. 4. Steady state drop size distribution and interfacial area (inset) obtained for the W/O (blue, upward triangles), Ref (gray, pentagons), and O/W (yellow, downward triangles) dispersed phase, indicated by the subscript d . The Kolmogorov-Hinze scale d_H is indicated with a vertical black dashed line, while the two analytical scaling laws, $d_{eq}^{-3/2}$ for the coalescence-dominated regime, and $d_{eq}^{-10/3}$ for the breakage-dominated regime, are reported with black solid lines. Experimental [53–55] and numerical [19,56–58] results are included for comparison with black symbols. The drop diameter is normalized by the Kolmogorov-Hinze scale for each case.

where ϵ is the dissipation at the channel center. To allow a comparison with literature results, experimental [53–55] and numerical [19,56–58] data are included in the figure (black symbols), reported in arbitrary units due to the different normalizations used. Additionally, the analytical scaling laws for the coalescence-dominated regime, $d_{eq}^{-3/2}$, and for the breakage-dominated regime, $d_{eq}^{-10/3}$, are reported with black solid lines. For each DSD, the drop diameter is normalized by the Kolmogorov-Hinze scale (estimated for the literature data, when not enough information is provided). The DSDs obtained in the present work show a reasonable agreement with literature results, as well as with the analytical scalings. Comparing the W/O, Ref, and O/W cases, we observe that the DSDs appear rather similar to each other. Indeed, in the inertia-dominated regime, drop deformation arises from a balance between external turbulent forcing and internal viscous damping, alongside surface tension effects [61]. When transitioning from W/O to O/W emulsions (corresponding to an increase in drop viscosity), internal viscous damping is enhanced. Simultaneously, the increase in shear Reynolds number from $Re_\tau = 150$ to $Re_\tau = 600$ intensifies the external turbulent forcing. These two competing effects seem to counterbalance each other, in the range of viscosity ratio and Reynolds number considered. Overall, the analysis of the DSD and interfacial area evolution indicates that the interface dynamics is only weakly affected by the type of emulsion considered. This suggests that the modulation of heat transfer due to modifications of the drop size distribution and the consequent interfacial area (bottom arrow in Fig. 3) plays a minor, and likely negligible, role.

2. Phase-conditioned characterization of the carrier and drop flow fields

To investigate the influence of the flow field on the temperature field (upper arrow of Fig. 3), we characterize the velocity field in the two phases. A first qualitative analysis is done considering

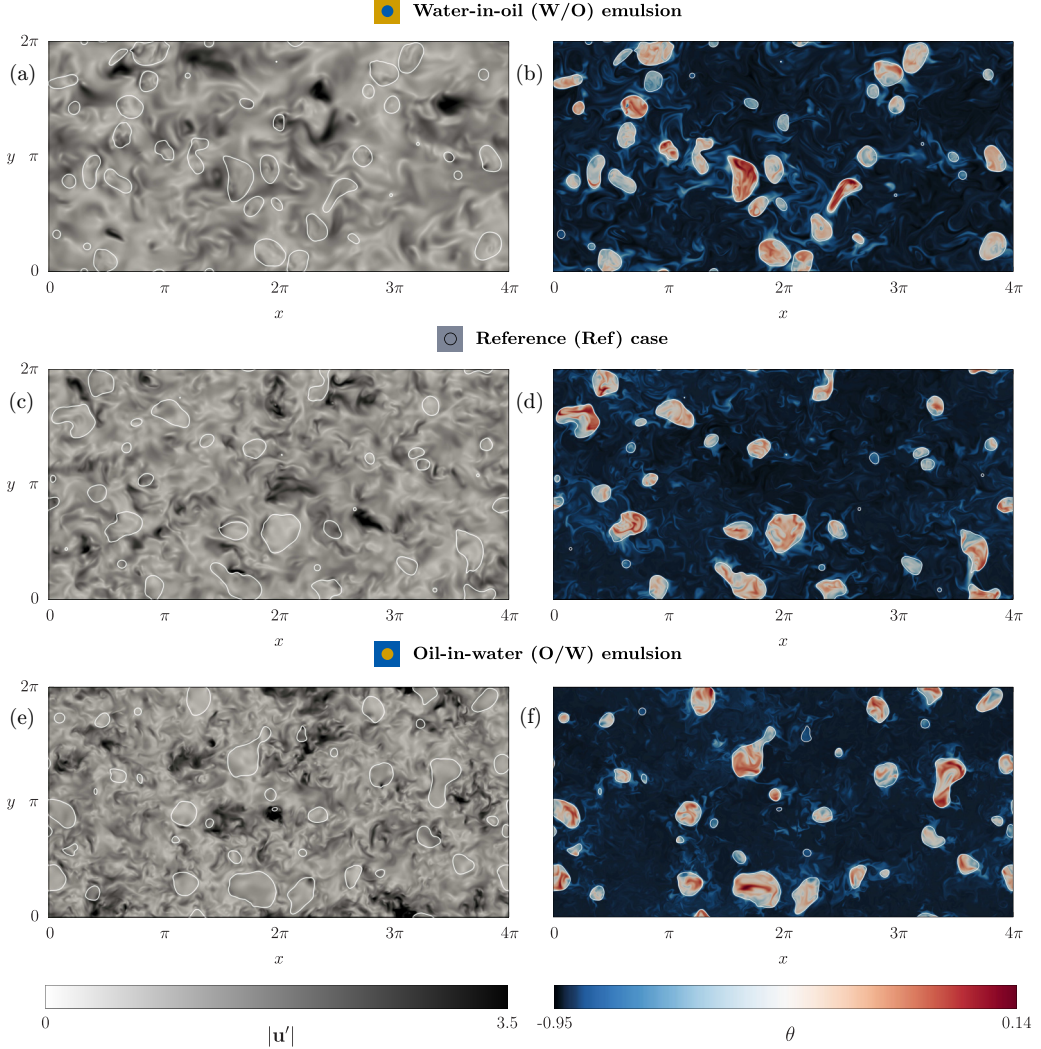


FIG. 5. Instantaneous visualizations of the velocity fluctuation magnitude field (b), (d), (f) and temperature field (a), (c), (e), for the W/O [(a) and (b)], Ref [(c) and (d)], and O/W [(e) and (f)] cases, on an x - y plane located at the channel center for $t = 6$. The velocity fluctuation is represented with a white-black colormap (white, low; black, high) while the temperature field is shown with a blue-red colormap (blue low; red high). The drops interface (isocontour $\phi = 0$) is marked by a white thin line.

Fig. 5, which shows the instantaneous visualizations of the velocity fluctuation magnitude and temperature fields, on an x - y plane at the channel center ($z = h$), at time $t = 6$. The velocity fluctuation magnitude (white-low; black-high) is shown in the left column, while the temperature (blue-low; red-high) is shown in the right column; each row refers to a different case. The drops interface, identified by the isocontour $\phi = 0$, is represented with a white thin line.

In the left column, significant changes are observed among the three cases in both the carrier and dispersed phases. In the carrier phase, as the shear Reynolds number increases from $Re_\tau = 150$ (W/O) to $Re_\tau = 300$ (Ref) and further to $Re_\tau = 600$ (O/W), the velocity gradients become sharper and the range of turbulent scales broadens, with the smallest scales decreasing in size, as expected. These modifications of the carrier flow closely resemble those observed in single-phase channel

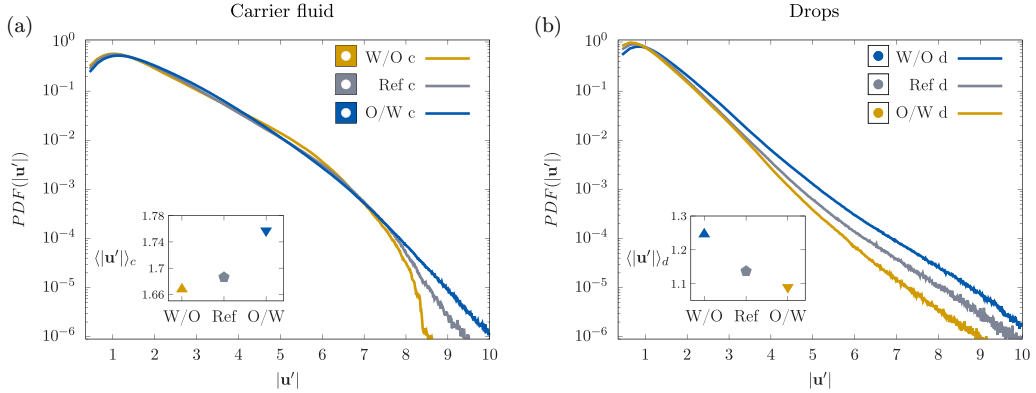


FIG. 6. Probability density function of the velocity fluctuation magnitude, phase-conditioned in the carrier fluid (a) and in the drops (b). In panel (a), yellow, gray, and blue colors are used for the oil (W/O), reference (Ref), and water (O/W) carrier phases, respectively, indicated by the subscript c ; in panel (b), blue, gray, and yellow colors refer to the water (W/O), reference (Ref), and oil (O/W) drops, respectively, indicated by the subscript d . The insets show the mean value of the velocity fluctuation magnitude conditioned in the two phases.

flows when increasing the shear Reynolds number [62]. An opposite trend is observed in the internal drop flow, where the drop viscosity progressively increases from top (W/O) to bottom (O/W). In the W/O case, the white-to-black contrasts are more intense and distributed over smaller scales than in the reference case, and even more so than in the O/W case. This suggests that the turbulence intensity decreases from the water drops to the reference drops and further to the oil drops.

Turning to the temperature fields (right column), all cases exhibit a similar range of temperature values, and the temperature difference between the drop and the carrier phase is approximately the same. This indicates that all systems are at a comparable stage of the thermal transient, in agreement with the previously observed global thermal behavior. A qualitative resemblance between the flow structures (left column) and the scalar structures (right column) is observed in all cases. In particular, the range of scales present in the velocity field directly influences the characteristic size of the filament-like structures in the temperature field. These temperature striations are largest in the W/O case (top) and become progressively smaller in the O/W case. This trend can be attributed to the different extents of the inertial-convective and viscous-convective ranges across the cases in the temperature field. Interestingly, the smallest characteristic length scales exhibited by the temperature field are similar in all cases. This can be traced back to the Péclet number, which is kept constant across the simulations. As a consequence, situations in which the flow structures display larger characteristic sizes (e.g., when either the carrier or the dispersed phase is oil) are compensated by the larger Prandtl number adopted in the corresponding phase. The only exception is the O/W case, for which the temperature structures in the dispersed phase are slightly larger than those observed in the other configurations. This deviation can be attributed to the higher viscosity of the oil droplets and to the confinement imposed by the droplet interface, which inhibits the development of a fully turbulent state.

To quantify the qualitative observations of the flow field, we analyze the probability density function (PDF) of the magnitude of the velocity fluctuations, conditioned on the phases, i.e., computed separately for the carrier fluid and for the drops. Analogously to the previous sections, lines related to the oil phase (carrier fluid for W/O and dispersed phase for O/W) are shown in yellow, those related to the water phase (dispersed phase for W/O and carrier fluid for O/W) are shown in blue, while results of the reference case are reported in gray. Figure 6 shows the PDF of the velocity fluctuations for the carrier phase [Fig. 6(a)] and for the dispersed phase [Fig. 6(b)]. All PDFs are time-averaged after the drop size distribution has reached a statistically steady state. Regarding the

carrier phase (left panel), the three cases exhibit similar behaviors in the range of fluctuations below $|\mathbf{u}'| \sim 7$, but visible deviations in the far tails of the distributions. In particular, moving from the oil carrier phase (W/O, yellow line) to the water carrier phase (O/W, blue line), the likelihood of observing very large velocity fluctuations increases. This behavior can be attributed to the higher Reynolds number of the carrier phase when transitioning from W/O to O/W, which enhances flow intermittency and therefore increases the likelihood of extreme events [63,64]. Consistently, the mean value of the velocity fluctuations increases by 5% from the W/O to O/W case, as shown in the inset of Fig. 6(a). Considering the dispersed phase (right panel), visible differences are present between the three cases over the entire range of fluctuations. Moving from oil drops (O/W, yellow line) to water drops (W/O, blue line), the distribution of velocity fluctuations progressively widens. This indicates that turbulence within the dispersed phase is more intense in water than in oil—as expected—and confirms the qualitative trends observed previously. The mean value of the velocity fluctuation magnitude, reported in the inset of Fig. 6(b), decreases by about 10% from the W/O to the O/W case, in accordance with the PDFs behavior. Compared to the PDFs computed for the carrier phase [Fig. 6(a)], the dispersed phase PDFs differ in several aspects [Fig. 6(b)]. First, while carrier-phase PDFs diverge only at very low probability levels, the dispersed-phase PDFs separate almost immediately. Second, the shapes of the distributions differ: carrier-phase PDFs show a convex shape, whereas dispersed-phase PDFs are characterized by a concave shape. This suggests that, inside the drops, very large velocity fluctuations—and consequently large velocity gradients and high dissipation levels—are less likely to occur. This observation is consistent with the absence of flow and thermal structures characterized by very small length scales observed in Figs. 5(e) and 5(f).

To further characterize the flow field in the two phases, we analyze the second-order longitudinal structure function of the velocity field, phase-conditioned in both the carrier fluid and the drops. This quantity is selected to evaluate the distribution of kinetic energy across spatial scales in the dispersed and carrier phases, which are closely linked to the scales governing heat mixing. In particular, the structure function is preferred over the one-dimensional power spectrum, as it can be evaluated separately in the dispersed and carrier domains without requiring domain periodicity and without complications arising from interfacial discontinuities [33,65]. The phase-conditioned second-order longitudinal structure function is defined as

$$\langle \Delta u^2 \rangle = \langle [u(x+r) - u(x)]^2 \rangle_{c,d}, \quad (16)$$

where r is the streamwise (longitudinal) separation distance. The bracket $\langle \cdot \rangle_{c,d}$ denotes a phase-conditioned average, subsequently averaged in time. To condition the structure function on a given phase, velocity differences are computed between pairs of points separated by a distance r and belonging to the same phase (i.e., having phase-field values of the same sign). In the case of drops, the point pairs are further constrained to belong to the same individual drop, under the assumption that flow structures within a drop can interact directly only with structures inside the same drop.

Figure 7 shows the second-order longitudinal structure functions of the carrier fluid [Fig. 7(a)] and of the drops [Fig. 7(b)], averaged over the x - y plane at the channel center ($z = h$) and compensated according to the inertial-range scaling $r^{2/3}$, following Kolmogorov theory [60]. Single-phase simulations at $\text{Re}_\tau = 150, 300$, and 600 , together with experimental results at $\text{Re}_\tau = 180$ [66], are included for reference. Solid lines (yellow, blue and gray for oil, reference and water phases, respectively) are used for the multiphase systems, dot-dashed lines indicate the single-phase cases, while black diamonds identify the experimental results. The star superscript, $*$, denotes normalization by Kolmogorov scales. Specifically, the separation distance r and the structure functions have been normalized by the Kolmogorov length and velocity scales, respectively, phase-averaged at the channel central plane (thus $r_{c,d}^* = r/\eta_{c,d}$ and $\langle \Delta u^{*2} \rangle_{c,d} = \langle \Delta u^2 \rangle_{c,d}/u_{k,c,d}^2$). In dimensionless form, the Kolmogorov length scales for the carrier fluid and the drops are computed as

$$\eta_{k_c} = \left(\frac{1}{\text{Re}_\tau^3 \epsilon_c} \right)^{1/4}, \quad \eta_{k_d} = \left(\frac{\mu_r^3}{\text{Re}_\tau^3 \epsilon_d} \right)^{1/4}, \quad (17)$$

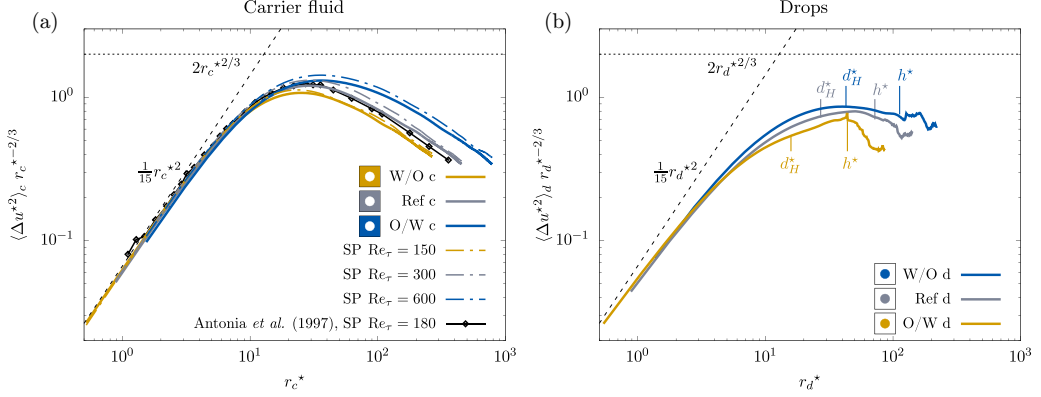


FIG. 7. Second-order longitudinal structure function at $z = h$, phase-conditioned in the carrier phase (a) and in the dispersed phase (b). In panel (a), yellow, gray, and blue colors are used for the oil (W/O), reference (Ref), and water (O/W) carrier phases, respectively, indicated by the subscript c ; in panel (b), blue, gray, and yellow colors refer to the water (W/O), reference (Ref), and oil (O/W) drops, respectively, indicated by the subscript d . Structure functions of the single-phase simulations (dash-dotted lines) and of single-phase experimental results obtained by Antonia *et al.* [66] (black diamonds) are included as a reference in panel (a). The Kolmogorov-Hinze scale and the channel half-height are reported as reference scales in panel (b). The dissipative and inertial range scalings, according to Kolmogorov theory for homogeneous isotropic turbulence, are indicated by dashed and dotted lines, respectively.

while the corresponding Kolmogorov velocity scales are

$$u_{kc} = \left(\frac{\epsilon_c}{\text{Re}_\tau} \right)^{1/4}, \quad u_{kd} = \left(\frac{\mu_r \epsilon_d}{\text{Re}_\tau} \right)^{1/4}, \quad (18)$$

where ϵ_c and ϵ_d denote the average phase-conditioned turbulent dissipation rates of the carrier fluid and of the drops, respectively. The classical Kolmogorov scalings for homogeneous and isotropic turbulence in dimensionless form, namely $\langle \Delta u^2 \rangle = \frac{1}{15} r^{*2}$ in the dissipative range and $\langle \Delta u^2 \rangle = C r^{*2/3}$ in the inertial range, with $C \simeq 2$ [66], are reported in Figs. 7(a) and 7(b). In Fig. 7(b), the Kolmogorov-Hinze diameter d_H^* and the channel height h^* are also shown for reference, with $d_H^* = d_H / \eta_{kd}$ and $h^* = h / \eta_{kd}$. The carrier-fluid structure functions exhibit a behavior similar to that of the corresponding single-phase flows at the same shear Reynolds number, with only a slight downward shift. This shift can be attributed to the lower energy level of the carrier phase compared to the single-phase flow, as part of the turbulent kinetic energy is absorbed by interface deformation (i.e., surface energy). In the dissipative range, the collapse onto the classical Kolmogorov scaling indicates homogeneous and isotropic small-scale behavior, in agreement with Antonia *et al.* [66]. At inertial scales, the curves progressively approach the homogeneous-isotropic limit and display an increasingly extended $r^{*2/3}$ plateau as the shear Reynolds number increases, consistently with experimental observations [66]. The drops structure functions display an overall trend analogous to that of the carrier and single-phase flows: they collapse at small scales and gradually approach the homogeneous-isotropic limit at inertial scales, with a progressively wider inertial-range plateau, as the inner drop Reynolds number increases. However, marked differences with respect to the carrier-phase structure functions are observed. All curves exhibit a smooth behavior only up to $r_d^* \sim h^*$, whereas for $r_d^* \gtrsim h^*$ they rapidly decrease and display significant oscillations. This behavior reflects the fact that drops extending in the streamwise direction beyond the channel height h are rarely observed. As a consequence, the contribution of the largest scales is strongly reduced due to the confinement imposed by the finite drop size. In addition, the drops structure functions attain systematically lower values, corresponding to lower turbulent energy levels, at all scales r^* .

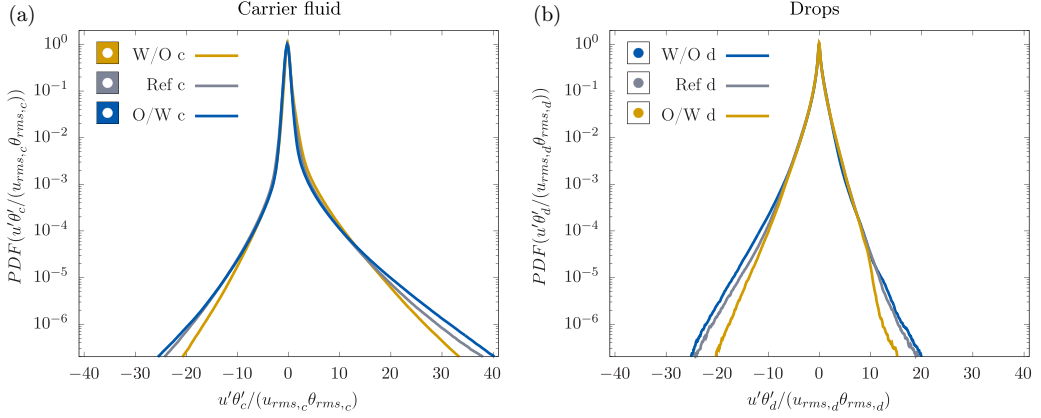


FIG. 8. Probability density function of the convective turbulent heat flux in streamwise direction. In panel (a), yellow, gray and blue colors are used for the oil (W/O), reference (Ref), and water (O/W) carrier phases, respectively, indicated by the subscript c ; in panel (b), blue, gray, and yellow colors refer to the water (W/O), reference (Ref), and oil (O/W) drops, respectively, indicated by the subscript d .

compared to the carrier fluid. Since structure functions can be interpreted as the cumulative energy of eddies of size $\sim r$ or smaller, the reduced energy in the drop flow is primarily associated with the different behavior of the dissipative scales, where a clear deviation from the classical $r^{\star 2}$ scaling is observed. This deviation indicates weaker small-scale velocity gradients inside the drops than in the carrier and single-phase flows, and can be attributed to the modulation induced by surface tension forces, which damp turbulent fluctuations. The observed behavior of the structure functions can be interpreted also by associating a Reynolds Taylor number to the carrier and dispersed flow field, namely $Re_{\lambda c}$ and $Re_{\lambda d}$. Estimated values based on phase-conditioned turbulent dissipation, $\epsilon_{c,d}$, and root-mean-square velocities, $u_{rmsc,d}$, give the following values: $Re_{\lambda c} \simeq 20$ and $Re_{\lambda d} \simeq 37$ for the W/O system, $Re_{\lambda c} \simeq 30$ and $Re_{\lambda d} \simeq 20$ for Ref system, and $Re_{\lambda c} \simeq 44$ and $Re_{\lambda d} \simeq 11$ for the O/W system. These values confirm that turbulence intensity is consistently higher in the less viscous phase, irrespective of whether it is the dispersed or the carrier phase. Interestingly, the Reynolds numbers in the dispersed phase are always lower than those in the carrier phase (comparing the same fluid, namely water, oil or the reference fluid). Overall, the structure-function behavior indicates that the velocity field inside the drops is characterized by reduced homogeneity and isotropy, as well as by lower turbulent energy levels compared to the carrier and single-phase flows, owing to confinement and interfacial modulation effects.

3. Flow field effects on mixing and global heat transfer

Having characterized the flow field in the different cases, we now examine how flow modifications affect the heat transfer process. To this aim, we compute the probability density function of the convective turbulent heat flux in the streamwise direction, normalized by the velocity and temperature RMS. The carrier and drop velocity RMS, $u_{rmsc,d}$, is computed from velocity fluctuations with respect to the mean streamwise velocity at each channel plane, whereas the carrier and drop temperature RMS, $\theta_{rmsc,d}$, is evaluated with respect to the corresponding phase-averaged temperature. For both quantities, spatial averaging is performed separately within the carrier and dispersed domains. Figure 8 shows the PDFs for the carrier fluid in Fig. 8(a), and for the dispersed phase in Fig. 8(b) (with yellow, blue, and gray colors for oil, reference, and water phases, respectively). For each phase, the W/O, Ref, and O/W cases differ only in the tails of the PDFs, indicating variations in extreme events, whereas the core of the distributions remains essentially unchanged. In the carrier fluid, the PDF widens as the shear Reynolds number increases (from W/O to O/W). A Reynolds number effect is also observed within the drops, where the PDF broadens when

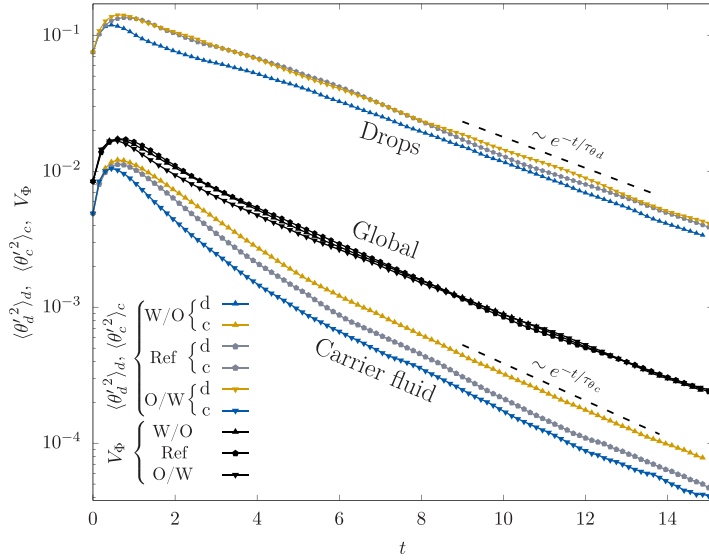


FIG. 9. Time evolution of the phase-conditioned temperature variance and of its volume-weighted average for the W/O, Ref, and O/W cases. The water, the reference, and the oil phases are reported with blue, gray, and yellow colors, respectively, for both drops and carrier fluid; the black color refers to the entire two-phase system. The W/O, Ref, and O/W cases are marked with upward triangles, pentagons, and downward triangles symbols, respectively. The subscripts d and c identify the drops and carrier fluid contributions. The exponential decays of the phase-conditioned temperature variances are indicated by dashed lines and are characterized by diffusive timescales $\tau_{\theta_c} \simeq 3.17$ and $\tau_{\theta_d} \simeq 3.82$.

moving from O/W to W/O. Notably, in the dispersed phase the three curves depart from each other asymmetrically between the left and right branches of the PDF. This behavior may be ascribed to the small slip velocity between the drops and the surrounding carrier fluid; this explanation, however, remains speculative, as the asymmetry is observed only at low probability levels ($\sim 10^{-3}$). Beyond this, we observe that this departure occurs at slightly larger probability values, similarly to what is observed for the PDF of the velocity fluctuation magnitude in Fig. 6(b). This behavior indicates that, in both the carrier fluid and the drops, streamwise velocity fluctuations promote more intense convective transport and a stronger coupling with temperature fluctuations as the shear or inner drop Reynolds number increases. Despite these differences, the variations observed in the PDF tails appear to have a negligible impact on the macroscopic heat transfer. This can be attributed to two main reasons. First, the core of the PDFs is unchanged across the different cases, and deviations occur only for events with very low probability, with relatively small differences between the curves. Second, the observed trends act in opposite directions within the same system (e.g., in the W/O case the likelihood of extreme events decreases in the carrier phase while increasing in the dispersed phase), suggesting the presence of a compensation mechanism that balances the contribution of extreme events.

To assess the presence of a compensation mechanism that maintains the robustness of heat transfer when the phases are switched, we examine the temporal evolution of the temperature variance in the carrier fluid and in the drops, $\langle \theta_c'^2 \rangle_c$ and $\langle \theta_d'^2 \rangle_d$; the phase-conditioned temperature fluctuations have been computed as

$$\theta'_c = \theta - \langle \theta \rangle_c, \quad \theta'_d = \theta - \langle \theta \rangle_d, \quad (19)$$

for the continuous and dispersed phase, respectively. Figure 9 illustrates the time evolution of the phase-conditioned temperature variance for both carrier fluid and drops, as well as its

volume-weighted average responsible for their global effect, for the W/O, Ref, and O/W cases. The W/O, Ref, and O/W cases are shown with upward triangles, pentagons and downward triangles, respectively; colors (yellow for oil, blue for water and gray for the reference case) identify the different phases, while black is used for global results. A clear separation is observed between the drops and carrier fluid variances; however, all curves exhibit a similar temporal evolution characterized by a monotonic decrease. The only exception occurs during the initial phase ($0.3 < t < 4$), when the system departs from the initial uniform temperature state. For $0.3 < t < 6$, the temperature variance starts to decrease monotonically for all cases and, specifically, the curves decay at a slightly different rate, diverging between each other. In particular, the decay rate is higher (in magnitude) when the lower viscosity fluid is considered (water). Hence, temperature variance decays faster for the water carrier phase of the O/W case and for the water drops of the W/O case. After $t \simeq 8$, all the lines decay over time with a constant decay rate thus resembling an exponential decay, as observed in Fig. 2(b) for the scalar dissipation rate. We further observe that the decay rate of the temperature variance in the carrier fluid is slightly higher than that in the droplet phase. The decay of both the carrier-fluid and droplet temperature variances follows an exponential scaling law, with characteristic timescales $\tau_{\theta c} \simeq 3.17$ and $\tau_{\theta d} \simeq 3.82$, respectively, confirming the faster decay in the carrier phase.

To understand how the different levels of temperature variance obtained in the different phases sum up to give a global contribution, we can exploit the phase-conditioned budget equation. By applying the phase-conditioned average, we obtain the following equations:

$$\frac{\partial \langle \theta_d'^2 \rangle_d}{\partial t} + \frac{\partial \langle \theta \rangle_d^2}{\partial t} = \mathcal{F}_d - \epsilon_{\theta d}, \quad (20)$$

$$\frac{\partial \langle \theta_c'^2 \rangle_c}{\partial t} + \frac{\partial \langle \theta \rangle_c^2}{\partial t} = \mathcal{F}_c - \epsilon_{\theta c}. \quad (21)$$

For each equation, the left-hand side is composed of two terms: the first term is the time variation of the phase-conditioned temperature variance, the second term is related to the time variation of the phase-conditioned mean temperature. On the right-hand side, the first term represents the diffusive flux at the interface, while the second term is the phase-conditioned scalar dissipation rate. The diffusive fluxes are expressed as

$$\mathcal{F}_d = \frac{2}{\text{Pe}} (\langle \nabla \cdot \langle \theta \rangle_d \nabla \theta_d' \rangle_d + \langle \nabla \cdot \theta_d' \nabla \theta_d' \rangle_d), \quad \mathcal{F}_c = \frac{2}{\text{Pe}} (\langle \nabla \cdot \langle \theta \rangle_c \nabla \theta_c' \rangle_c + \langle \nabla \cdot \theta_c' \nabla \theta_c' \rangle_c), \quad (22)$$

while the phase-conditioned scalar dissipation rates are defined as

$$\epsilon_{\theta d} = \frac{2}{\text{Pe}} \langle |\nabla \theta_d'|^2 \rangle_d, \quad \epsilon_{\theta c} = \frac{2}{\text{Pe}} \langle |\nabla \theta_c'|^2 \rangle_c. \quad (23)$$

By multiplying each phase-conditioned budget equation by the respective phase volume fraction and summing them up, after some algebraic manipulations we obtain

$$\frac{\partial \left(\overbrace{\langle \Phi \theta_d'^2 \rangle_d + (1 - \Phi) \langle \theta_c'^2 \rangle_c}^{V_\Phi} \right)}{\partial t} + \frac{\partial \left(\overbrace{\langle \Phi \theta \rangle_d^2 + (1 - \Phi) \langle \theta \rangle_c^2}^{M_\Phi} \right)}{\partial t} = -\epsilon_\theta, \quad (24)$$

which corresponds to Eq. (12). Note that the diffusive fluxes cancel out since the energy lost through the interface by the drops corresponds to the energy gained by the carrier fluid. Given that the mean temperature evolution is the same for all cases [Fig. 2(a)], the volume-weighted average of the mean temperature, M_Φ , is also equal in all cases. Consequently, the phase-conditioned temperature variances must balance out, yielding an equal volume-weighted average V_Φ across the three cases, to produce the same global response. This is confirmed by Fig. 9, where V_Φ (e.g., for W/O, the combined contribution of the water drops and the oil carrier phase) collapses onto the same curve for all configurations. Overall, this observation demonstrates that the local temperature differences

between the W/O, reference, and O/W systems—generated by the distinct flow structures present in the two phases, as revealed by the phase variances and the PDFs of the convective heat flux—compensate each other. As a result, the volume-weighted average temperature variance remains nearly identical, leading to equivalent global thermal behavior.

V. CONCLUSIONS

In this work, we have performed direct numerical simulations of turbulent heat transfer in oil-water emulsions with reversed viscosity contrast, considering both water-in-oil and oil-in-water configurations at matched Péclet number. By coupling turbulence-resolving DNS with a phase-field formulation, we have investigated how switching the oil and water phase, with one phase dispersed in the other one, affects scalar mixing across a wide range of spatial and temporal scales. The thermal field was initialized simultaneously with an initially uniform drop distribution, so that thermal equilibration and drop size redistribution evolved concurrently during the transient. While this implies that the early thermal response is coupled to the initial evolution of the interfacial area, the latter undergoes its most significant changes only at early times and follows a similar evolution across all configurations, supporting the robustness of the comparative trends discussed in this work. Reversing the dispersed and carrier phases strongly modifies the local turbulent dynamics. Velocity fluctuations, turbulent heat flux and scalar variance are redistributed between the droplet interior and the surrounding fluid in a manner controlled by viscosity contrast and phase occupancy. Phase-conditioned structure functions demonstrate that turbulence inside the drops and in the carrier phase follows different scaling behavior, revealing distinct mixing mechanisms in the two regions. These local differences reorganize such that the reduced mixing efficiency within the more viscous phase is compensated by enhanced advection and scalar transport in the less viscous phase, leading to comparable macroscopic heat transfer rates and similar thermal equilibration times in the two emulsions. As a result, the global thermal response of the system is largely insensitive to an interchange of the dispersed and carrier phases, despite substantial differences in the underlying turbulent structure. These findings show that global transport coefficients in turbulent emulsions cannot be inferred directly from local turbulence intensity or scaling behavior alone. Instead, they emerge from a redistribution of mixing activity between phases induced by viscosity contrast. This has important implications for the modeling of heat and mass transfer in multiphase turbulent flows, where phase-conditioned dynamics may differ strongly while macroscopic transport remains robust.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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