2-phase Interfacial, Droplet, Bubble Turbulence and Combustion in the Normal and Microgravity Conditions

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“Turbulence Theory in spite of very complicated mathematics has very limited Physical Concepts”
V.M.Ievlev

Introduction

Turbulence is very common phenomena and in spite of more than 100 years research still has many conundrums. Physical approach abd understading phenomena usually based on simple examples and step by step increase the complexity of models until we reach real phenomena. From this point of view the simplest model is incompressible fluid. Studying turbulence better start from the 1D fluid flows,but due to discontinuity equation $(\partial u_i)/(\partial x_i) = 0$ it follows $u_i = 0$ for homogeneous flow. We consider developing turbulence in 2D models, of Homogeneous Isotropic then 3D taking into account consequently Gravity,Vibrations, RTI - Kapitsa Pendilum and Multiphase Turbulence in Droplets, Bubbles and Interface Turbulence, Reconnections, Coherent Structures, Intermittance are considered in Multiphase Turbulence,

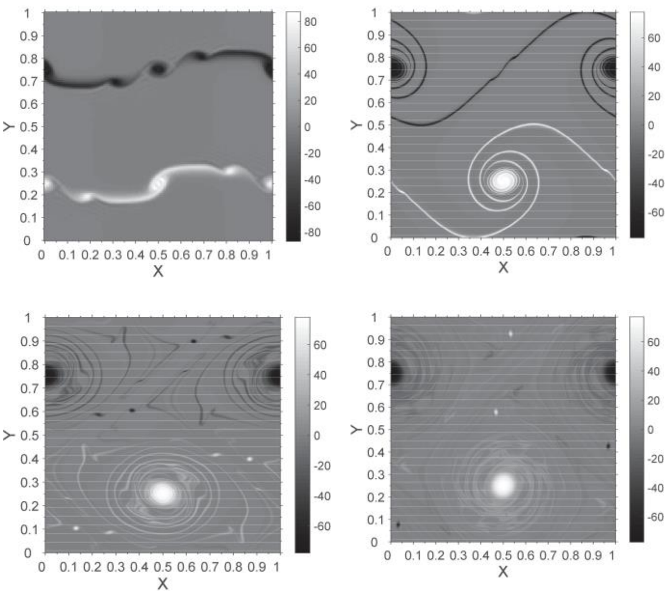


Fig.1. 2D Turbulent Shear Flow Dynamics

Nature of Hydrodynamics Turbulence

Next simple model is 2D turbulence where the consideration starts from the homogeneous isotropic turbulence and cascade formation from energy to inertial and viscous intervals are considered/ It is found that energy flux in spectral space is forming due to nonlinear terms with essential Obukhov time scales and viscous dissipation play the role of BC for energy spectrum. This result gives the approach to establish specific rotational energy cascade and is generalized to 3D turbulence for different types of dissipation. As an example we considered the shir

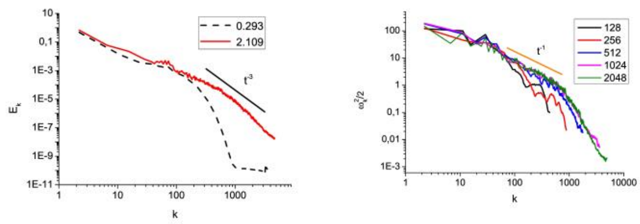


Fig.2. 2D Turbulence Spectra Enstrophy and KE

General Apprach to Multiphase FlowsTurbulence

Generalized transport equation with the boundary conditions inserted into the eqiations

$$\frac{\partial}{\partial t}\varphi_a\rho\xi + \nabla\cdot\varphi_a\rho\xi\mathbf{u} = -\nabla\cdot\varphi_a\mathbf{i}_\xi + \varphi_a Q_{\xi V} + \varphi_a Q_{\xi S}\delta_S + $$
$$+ \rho_a\xi(\mathbf{u}_a - \mathbf{D})\cdot\nabla\varphi_a + \mathbf{i}_\xi\cdot\nabla\varphi_a. \qquad (39)$$

For the momentum equation $\xi = \mathbf{u}$, $\mathbf{i}_\xi = \mathbf{T}$, $Q_{\xi V} = \rho g$, $Q_{\xi S} = \alpha\kappa n$ we find out

$$\frac{\partial}{\partial t}\varphi_a\rho\mathbf{u} + \nabla\cdot\varphi_a\rho\mathbf{u}\mathbf{u} = \nabla\cdot\varphi_a T + \varphi_a\rho\mathbf{g} + \varphi_a\alpha\kappa\mathbf{n}\delta_S + $$
$$+ \rho_a\mathbf{u}_a(\mathbf{u}_a - \mathbf{D})\cdot\nabla\varphi_a - \mathbf{T}\cdot\nabla\varphi_a. \qquad (40)$$

For the energy equation $\xi = e$, $i_\xi = j_e$, $Q_{\xi S} = \alpha\kappa D$:

$$\frac{\partial}{\partial t}\varphi_a\rho e + \nabla\cdot\varphi_a\rho e\mathbf{u} = -\nabla\cdot\varphi_a\mathbf{j}_e + \varphi_a\alpha\kappa D\delta_S + $$
$$+ \rho_a e_a(\mathbf{u}_a - \mathbf{D})\cdot\nabla\varphi_a + \mathbf{j}_{ae}\cdot\nabla\varphi_a. \qquad (41)$$

Multiphase Turbulence Moments Equations

In this subsection we will average multi-phase equations (42, 43) with the next averaged variables:

$$\Phi_a = <\varphi_a>, \quad \Psi_a = <\varphi_a\psi> \quad \textit{for any} \quad \psi \quad ,$$
$$u_a = \varphi_a v_a, \quad u_a = U_a + u'_a,$$
$$U_a = <u_a> = <\varphi_a v_a>, \quad u'_a = (\varphi_a v_a)'$$

Below to simplify notations for Stokes stress tensor in some formulas, where evident, we put $\sigma^S \equiv \sigma$.

Averaging local phase mass (42) and momentum (43) equations we find out MPRANS (Multi-Phase Reynolds Averaged Navier-Stokes) equations for multi-phase flow.

$$\frac{\partial \Phi_a}{\partial t} + \nabla \cdot U_a = 0, \tag{51}$$

$$\rho_a\left(\frac{\partial U_a}{\partial t} + \nabla \cdot U_a U_a\right) = -\nabla < \varphi_a p > + \nabla \cdot < \varphi_a \sigma > - \nabla \cdot \rho < u'u' > +$$

$$+\varphi_a \rho g + < \varphi_a \alpha \kappa \nabla \varphi_a > + < p \nabla \varphi_a > - < \sigma \cdot \nabla \varphi_a >,$$

Additional terms represents corrections to interfacial pressure and surface tension:

$$\Delta F_a^{pi} = < (p - p_a^i) \nabla \varphi_a > \neq 0, \tag{55}$$

$$\Delta F_a^{\alpha i} = \frac{\alpha}{2} < (\kappa - \kappa_a^i) \nabla \varphi_a > \neq 0. \tag{56}$$

Reynolds stresses in the used variables are

$$\sigma_a^R = -\rho < u'u' > . \tag{57}$$

Rewrite the equation (52) in the form

$$\rho_a\left(\frac{\partial U_a}{\partial t} + \nabla \cdot U_a U_a\right) = -\nabla p_a + \nabla \cdot (\sigma_a^S + \sigma_a^R) + \Phi_a \rho g + m_a,$$

where m_a is the phase momentum transfer force defined by

$$m_a = \left(p_a^i + \frac{\alpha}{2}\kappa_a^i\right)\nabla \Phi_a - \sigma_a^i \cdot \nabla \Phi_a + \Delta F_a^{\alpha i} + \Delta F_a^{pi}, \tag{59}$$

Finally the full set of equations for multi-phase flow consist of mass and momentum equations for each phase (51), (58) and the equation of full mass conservation which follows from the averaging the equation (36)

$$\sum_a \Phi_a = 1. \tag{60}$$

This set of equations slightly different from Drew [26] equations and more convenient for computer simulation.

Closures

This filtering process generates fewer equations than unknowns, and so further constitutive relations must be provided by m_a - forces due to a) viscous drag, b) wake and boundary layer formation, c) virtual mass and lift effects. S_a - subfilter length intraphasic stress terms should include a) dissipation of energy from resolved to unresolved scales (eddy viscosity model), b) back-scatter from unresolved to resolved scales c) Droplet induced turbulence, d) effect of stratification and buoyancy, e)expressions the p_a, κ_a and interfacial pressure and curvature p_a^i, κ_a^i.

As the first approximation we can use

$$p_a = \Phi_a p, \tag{65}$$

$$m_a = 0 \quad \{p_a^i = 0, \quad \kappa_a^i = 0, \quad \sigma_a^i = 0, \quad \Delta F_a^{\alpha i} = 0, \quad \Delta F_a^{pi} = 0\}. \tag{66}$$

Below we will discuss the closure for interfacial terms in more details.

We use eddy viscosity ideas to model the stress tensor σ_a

$$\boldsymbol{\sigma}_a = 2\rho_a(\Phi_a \nu_a^m + \nu_a^t)\mathbf{S}_a, \tag{67}$$

where

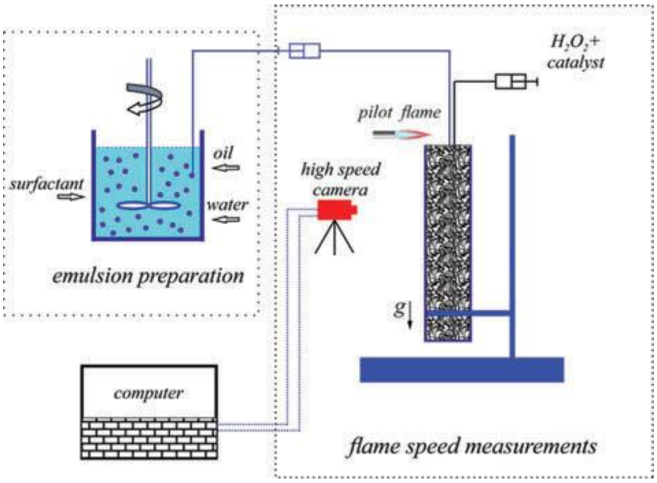
$$\mathbf{S}_a = \frac{1}{2}\left[(\nabla \mathbf{u}_a) + (\nabla \mathbf{u}_a)^T\right] \tag{68}$$

Here ν_a^m and ν_a^t are the molecular and turbulent viscosities of phase a. Smagorinsky type models, see [66] for example, relate ν_a^t to the second invariant of S_a, the spatial filter scale L and grid-size Δx. With $L = \Delta x$

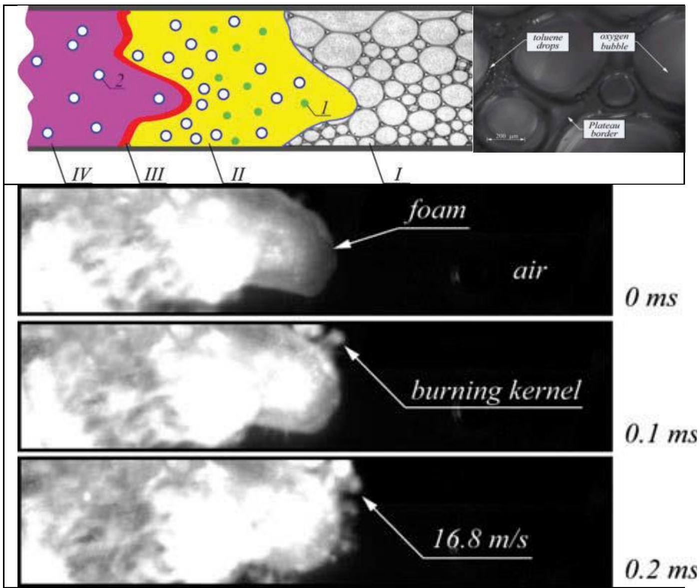
$$\nu_a^t = C_s^2 \Delta x^2 \left[\mathbf{S}_a : \mathbf{S}_a\right]^{1/2} \tag{69}$$

and C_s is the Smagorinsky constant ($C_s \approx 0.1 - 0.2$).

Multiphase scales



Inhomogeneous Interfacial Turbulence



Combustion of foam – droplets

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