Mechanisms of Atomization

in

Fluid-Fluid Channel Flows

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Outline

• Importance of atomization processes
• Basestate for stratified atomization
  – Sheared layer flow with waves
  – Some characteristics of waves and questions
• Linear stability for these flows
  – Some results and limitations
• Atomization Mechanisms

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Importance of atomization

- In annular flow, the entrained fraction can be 20-40% of the liquid (Fore and Dukler, 1995; Asali et al., 1985).
  - Current (mostly) empirical correlations are inadequate.

- What is known about atomization
  - Atomization occurs from solitary and roll waves (Woodmansee and Hanratty, 1968; Whalley, Hewitt & Terry, 1979).

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Importance of atomization

Specific applications

• Gas-liquid contacting
  • (novel process improvements (mixing/contacting) with ~$0 capital costs)
  • “Optimal” gas-liquid mass transfer process will involve some atomization, and some special overall fluid geometry

• Phase change process affected by liquid on the wall

• Pressure drop, transport rates in annular flow

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Starting geometry of interest

Two-fluid stratified flow

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Wave regime map

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Wave tracings across the transition

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Background wave field
Onset of Solitary waves
Solitary waves well above onset
Wave spectra across the transition

Figure 3. Interfacial wave spectra, $R_e = 10, \mu = 15$ cP

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Spectra as a function of distance

Data of Bruno and McCready, 1988
Wave transition as gas increases
Wave transition as gas increases (more)
Solitary waves in gas-liquid flow

\[ \mu = 12 \text{ cP}, \; Re_L = 12 \]

\[ Re_G = 19479 \]

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Solitary Wave Scaling

\[ \frac{(R-R_{\text{critical}})}{R_{\text{critical}}} \]

\[ \mu = 15 \text{ cP} \]
\[ \mu = 20 \text{ cP} \]

power law exponent = 1.35
power law exponent = 1.5

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Gas-liquid flow interfacial stability problem

turbulence model: k-ε

Solve the base state with either a smooth or rough interface (try to match data).

then

Solve the differential stability problem the best we can

Liquid-phase: $0 \leq y^* \leq d_1$

$$
\rho_1 \left[ \frac{\partial u_i^*}{\partial t^*} + u_j^* \frac{\partial u_i^*}{\partial x_j^*} \right] = - \frac{\partial p^*}{\partial x_i^*} + \rho_1 g \cdot \sin(\theta) + \frac{\partial}{\partial x_j^*}\left[ (\mu_1 + \mu_i^*) \left( 2s_{ij}^* \right) \right]
$$

$$
\rho_1 \left[ \frac{\partial k_i^*}{\partial t^*} + u_j^* \frac{\partial k_i^*}{\partial x_j^*} \right] = \frac{\partial}{\partial x_i^*}\left[ \left( \mu_1 + \frac{\mu_i^*}{\sigma_{ke}} \right) \frac{\partial k_i^*}{\partial x_i^*} \right] + \mu_i^* \left( 2s_{ij}^* \right) \frac{\partial u_i^*}{\partial x_j^*} - \rho_1 \varepsilon^* - 2\mu_i \left( \frac{\partial \sqrt{k_i^*}}{\partial x_i^*} \right)^2
$$

$$
\rho_1 \left[ \frac{\partial \varepsilon^*}{\partial t^*} + u_j^* \frac{\partial \varepsilon^*}{\partial x_j^*} \right] = \frac{\partial}{\partial x_i^*}\left[ \left( \mu_1 + \frac{\mu_i^*}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon^*}{\partial x_i^*} \right] + c_i f_i \mu_i^* \frac{\varepsilon^*}{k_i^*} \left( 2s_{ij}^* \right) \frac{\partial u_i^*}{\partial x_j^*} + 2\mu_i \left( \frac{\partial^2 u_i^*}{\partial x_j^* \partial x_i^*} \right)^2 - \rho_1 c_i f_i \frac{\varepsilon^2}{k_i^*}
$$

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Stability equations continued

as-phase: \( d_1 \leq y^* \leq d_1 + d_2 \)

\[
\rho_2 \left[ \frac{\partial u_i^*}{\partial t^*} + u_j^* \frac{\partial u_i^*}{\partial x_j} \right] = - \frac{\partial p^*}{\partial x_i^*} + \rho_2 g^* \sin (\theta) + \frac{\partial}{\partial x_j^*} \left[ (\mu_2 + \mu_i^*)(2s_{ij}^*) \right]
\]

\[
\rho_2 \left[ \frac{\partial k_i^*}{\partial t^*} + u_j^* \frac{\partial k_i^*}{\partial x_j} \right] = \frac{\partial}{\partial x_i^*} \left[ \left( \mu_2 + \frac{\mu_i^*}{\sigma} \right) \left( \frac{\partial k_i^*}{\partial x_i} \right) \right] + \mu_i^* (2s_{ij}^*) \frac{\partial u_i^*}{\partial x_j} - \rho_2 \epsilon^* - 2\mu_2 \left( \frac{\partial \sqrt{k_i^*}}{\partial x_i} \right)^2
\]

\[
\rho_2 \left[ \frac{\partial \epsilon_i^*}{\partial t^*} + u_i^* \frac{\partial \epsilon_i^*}{\partial x_i} \right] = \frac{\partial}{\partial x_i^*} \left[ \left( \mu_2 + \frac{\mu_i^*}{\sigma} \right) \left( \frac{\partial \epsilon_i^*}{\partial x_i} \right) \right] + c_1 f_i \rho_i^* e_i \frac{\partial u_i^*}{\partial x_i^*} \left( 2s_{ij}^* \right) \frac{\partial u_i^*}{\partial x_j^*} + 2\mu_2 \mu_i^* \left( \frac{\partial u_i^*}{\partial x_i} \right)^2 - \rho_2 c_1 f_i \frac{\epsilon_{ij}^*}{k_i^*}
\]

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\[ k=1 \text{ (liquid-phase)} \quad 0 \leq y \leq 1 \]
\[ k=2 \text{ (gas-phase)} \quad 1 \leq y \leq n_z + 1 \]

\[
\left( \frac{\mu_k u_{b,k}}{m_k} \right)'' + \left( \Gamma_{b,k} \hat{\phi}_k'' \right) + \alpha \hat{\phi}_k'' + \alpha^2 \Gamma_{b,k} \phi_k = i \alpha R \frac{r_k}{m_k} \left\{ \left(u_{b,k} - c\right) \left( \hat{\phi}_k'' - \alpha^2 \hat{\phi}_k \right) - u_{b,k} \phi_k \right\}
\]

\[
\left( \frac{\mu_k k_{b,k}}{m_k} \right)' + \mu_k u_{b,k}'' + \Gamma_{b,k} \left( \hat{k}_k'' - \alpha^2 \hat{k}_k \right) + \Gamma_{b,k} \hat{k}_k + 2 \frac{\mu_k u_{b,k}'}{m_k} \left( \hat{\phi}_k'' + \alpha^2 \hat{\phi}_k \right) + \frac{k_{b,k}'}{2} \left( \frac{k_{b,k}}{k_{b,k}'} \hat{k}_k - \hat{k}_k' \right) = i \alpha R \frac{r_k}{m_k} \left( \left(u_{b,k} - c\right) \left( \hat{k}_k - \hat{k}_k' \right) \right)
\]

\[
\left( \frac{\mu_k e_{b,k}}{m_k} \right)' - \Gamma_{b,k} \Gamma_{b,k} \left( e_{b,k}'' - \alpha^2 e_{b,k} \right) + \Gamma_{b,k} e_{b,k} + 2 c f \frac{\mu_k u_{b,k}'}{m_k} \left( \hat{\phi}_k'' + \alpha^2 \hat{\phi}_k \right) + r_i R c f_k \left( \frac{e_{b,k}}{k_{b,k}} \hat{k}_k - 2 \hat{e}_{b,k} \right)
\]

\[
+ \left( \frac{u_{b,k}''}{m_k} \right)' + 2 c f \frac{e_{b,k}}{k_{b,k}} \left( \mu_k + \dot{e}_{b,k} - \frac{m_{b,k} \mu_{b,k}'}{k_{b,k}} \hat{e}_k \right) = i \alpha R \frac{r_k}{m_k} \left( \left(u_{b,k} - c\right) \left( \hat{e}_k - \hat{e}_{b,k} \hat{\phi}_k \right) \right)
\]

\[
\mu_k = c f r_i R \frac{k_{b,k} \hat{k}_k}{k_{b,k}^2} \left( \frac{2 \hat{e}_k - k_{b,k}}{k_{b,k}} \hat{e}_{b,k} \right)
\]

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Stability Equations cont.

Boundary conditions

\[ \hat{\phi}_1 = \hat{\phi}_2 \]  
(3-18c)

\[ \hat{\phi}_1 + u_{b,1} \hat{h} = c \hat{h} \]  
(3-18d)

\[ \hat{\phi}_1' - \hat{\phi}_2' = \hat{h} \left( u_{b,1}' - u_{b,2}' \right) \]  
(3-18e)

\[ \hat{\phi}_1'' + \alpha^2 \hat{\phi}_1 + \hat{h} u_{b,1}'' = m_2 \left( \hat{\phi}_2'' + \alpha^2 \hat{\phi}_2 + \hat{h} u_{b,2}'' \right) \]  
(3-18f)

\[ \left( \hat{\phi}_1''' + \Gamma_{b,1} \hat{\phi}_1'' + u_{b,1} F_1'' - 3 \alpha^2 \hat{\phi}_1 \right) + i \alpha R \left( u_{b,1}' \hat{\phi}_1 - u_{b,1} \hat{\phi}_1' \right) - m_2 \left( \hat{\phi}_2''' + \Gamma_{b,2} \hat{\phi}_2'' + u_{b,2} F_2'' - 3 \alpha^2 \hat{\phi}_2 \right) \]  
(3-18g)

\[ - i \alpha r_2 R \left( u_{b,2}' \hat{\phi}_2 - u_{b,2} \hat{\phi}_2' \right) - i \alpha R \left[ \left( 1 - r_2 \right) F + \alpha^2 S \right] \hat{h} = i \alpha R c \left( r_2 \hat{\phi}_2' - \hat{\phi}_1' \right) \]  
(3-18h)

\[ k_1 = \varepsilon_1 = \mu_1 = k_2 = \varepsilon_2 = \mu_2 = 0 \]  
(3-18h)
How close is the base state?

Figure 4.7 $h^+$ - $Re_L$ correlation for horizontal gas-liquid channel flow. $Re_G = 4,000 - 15,000$

Bruno (1988) Experiments
Lin and Hanratty (1986)
friction factor model
Laminar Base state
K-ε model

$\mu_L = .92$ cp
$d = 2.54$ cm
Friction velocity -- Re

Figure 4.5 Friction velocity versus \(Re_G\) at constant \(Re_L\).
\[d = 2.54 \text{ cm}, \mu_L = 1 \text{ cp}, P=14.7 \text{ psia}, T=298 \text{ K}\]
Laminar growth rate scaling

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Wave growth in turbulent flow
some similarity to laminar flow?

\[
\frac{\omega d_i}{\nu^*} \propto \left( \frac{Re_G - Re_{G,\text{crit}}}{Re_{G,\text{crit}}} \right)
\]

- Laminar flow for both phases (Kuru, 1995)
  - \( h^* = 0.4, \lambda = 1 \text{ cm}, Re_L = 2844 \)
  - \( h^* = 0.3, \lambda = 1 \text{ cm}, Re_L = 1228 \)
  - \( h^* = 0.2, \lambda = 1 \text{ cm}, Re_L = 448 \)

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Atomization Mechanisms

(Woodmansee, Hanratty, 1969)

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Fig. 5. Ripples being lifted and shattered by 60 ft/sec airstream.
Rotating, Two-(matched density) liquid, Couette Flow, Wave Experiment

Outside cylinder is Plexiglas®, Inside cylinder is Aluminum painted black

Outside cylinder is rotated.

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Two-(matched density) liquid, rotating Couette device

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Rotating Couette experiment

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Wave map for rotating Couette flow experiment

- **stable long waves**
- Steady 2-D waves occur in most of this range

Legend:
- □ No waves
- △ steady periodic
- × unsteady waves
- ♦ solitary

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Atomization

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Figure 3: A roll wave for $m=0.0159$, $\sigma = 0.01 \, N/m$, $l = 0.66$, and $U_p = 84 \, cm/s$. (“Dark” phase is more viscous and it is being atomized)

$v_{Re_{light}} = 560 \quad Re_{dark} = 9.5$

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Figure 4: A sheet-like structure for $m=0.0159$, $\sigma = 0.01 \ N/m$, $l = 0.66$, and $U_p = 84 \ cm/s$. (“Dark” phase is more viscous and it is being atomized)
Figure 5: A sheet-like structure just prior to break off for $m=0.0159$, $\sigma = 0.01 \text{ N/m}$, $l = 0.66$, and $U_p = 84 \text{ cm/s}$. (“Dark” phase is more viscous and it is being atomized)
A series of frames 2 milliseconds apart showing the breakup.
A series of frames 2 milliseconds apart showing the breakup.
A series of frames 2 milliseconds apart showing the breakup.
Breakup Occurs

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The change in the height of the sheet $d/d_0$ as a function of time. (almost) Linear stretching is observed.
Conclusions

1. Atomization seems to be a generically important process that is not understood very well.
   - Making quantitative predictions is very difficult

2. Atomization in parallel two-layer flows will be associated with the waves that are already present.
   - Quantitative prediction of these waves is not possible at present

3. Even base-state and linear stability predictions need further work
   - This is at conditions much less severe than atomization occurs.
Conclusions

4. In the general case it is the more viscous fluid that is atomizing from crests of large waves
   - Lift and shatter
   - Stretch and break

5. There does not seem to be a reason that solitary waves (maybe not roll waves) can exist without significant atomization

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