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TWO–DIMENSIONAL ANALYSIS OF THE CRYSTALLIZATION OF HOLLOW COMPOUND PLASTIC FIBERS

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- $\qquad \qquad \Box$ Applications
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- Necessary: modelling of the drawing process of semi–crystalline hollow compound fibers.
- Previous studies are based on one–dimensional models of amorphous, slender fibers at very low Re and Bi numbers.
- **NO INFORMATION ABOUT TEMPERATURE** NON–UNIFORMITIES IN THE RADIAL DIRECTION.
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Involves the extrusion and drawing of a polymer cylinder. Four zones.

XXXX **Fiber tokeup** **1** Shear Flow Region.

- 2 Flow Rearrangement Region.
- **6** Melt Drawing Zone.
- **4** Solidification region.

 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right.$

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Mass conservation equation

$$
\nabla \cdot \mathbf{v}_i = 0 \qquad i = 1, 2,
$$

where $\mathbf{v} = u(r, x) \mathbf{e}_\mathbf{x} + v(r, x) \mathbf{e}_\mathbf{r}$

Linear Momentum conservation equation

$$
\rho_i \left(\frac{\partial \mathbf{v}_i}{\partial t} + \mathbf{v}_i \cdot \nabla \mathbf{v}_i \right) = -\nabla p_i + \nabla \cdot \boldsymbol{\tau}_i + \rho_i \cdot \mathbf{f}^m \qquad i = 1, 2,
$$

where $\mathbf{f}^m = g \, \mathbf{e}_\mathbf{x}$

Energy conservation equation

$$
\rho_i C_i \left(\frac{\partial T_i}{\partial t} + \mathbf{v}_i \cdot \nabla T_i \right) = -K_i \Delta T_i \qquad i = 1, 2,
$$

- Constitutive equations
	- **a** Rheology

$$
\tau = \mu \left(\nabla \mathbf{v} + \nabla \mathbf{v}^T \right) + \tau_p
$$

$$
\tau_p = 3c k_B T \left[-\frac{\lambda}{\phi} F(\mathbf{S}) + 2\lambda \left(\nabla \mathbf{v}^T : \mathbf{S} \right) (\mathbf{S} + \mathbf{I}/3) \right]
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Molecular orientation and crystallinity models

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Crystallization: Avrami–Kolmogorov's theory & Ziabicki's model

$$
\frac{\partial Y_i}{\partial t} + \mathbf{v}_i \cdot \nabla Y_i = k_{Ai}(\mathcal{S}_i) (Y_{\infty, i} - Y_i) \qquad i = 1, 2,
$$

where

$$
k_{Ai}(\mathcal{S}_i) = k_{Ai}(0) \exp (a_{2i} \mathcal{S}_i^2), \qquad i = 1, 2.
$$

Molecular orientation scalar order parameter

$$
\mathcal{S} \equiv \sqrt{\frac{3}{2} \left(\mathbf{S} : \mathbf{S} \right)} \qquad \mathbf{S} = \frac{1}{3} \cdot \text{diag} \left(S_{rr}, -\left(S_{rr} + S_{xx} \right), S_{xx} \right),
$$

Molecular orientation tensor equation: Doi–Edwards theory

$$
\begin{aligned} \mathbf{S}_{(1)} &= F(\mathbf{S}) + G(\nabla \mathbf{v}, \mathbf{S}), \\ F(\mathbf{S}) &= -\frac{\phi}{\lambda} \left\{ (1 - N/3) \, \mathbf{S} - N \left(\mathbf{S} \cdot \mathbf{S} \right) + N \left(\mathbf{S} : \mathbf{S} \right) \left(\mathbf{S} + \mathbf{I}/3 \right) \right\} \\ G(\nabla \mathbf{v}, \mathbf{S}) &= \frac{1}{3} \left(\nabla \mathbf{v} + \nabla \mathbf{v}^T \right) - 2 \left(\nabla \mathbf{v}^T : \mathbf{S} \right) \left(\mathbf{S} + \mathbf{I}/3 \right). \end{aligned}
$$

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$$
\Lambda_{(1)} = \frac{\partial \Lambda}{\partial t} + \mathbf{v} \cdot \nabla \Lambda - \left(\nabla \mathbf{v}^T \cdot \Lambda + \Lambda \cdot \nabla \mathbf{v}\right)
$$

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Crystallization: Avrami–Kolmogorov's theory & Ziabicki's model

$$
\frac{\partial Y_i}{\partial t} + \mathbf{v}_i \cdot \nabla Y_i = k_{Ai}(\mathcal{S}_i) (Y_{\infty, i} - Y_i) \qquad i = 1, 2,
$$

where

$$
k_{Ai}(\mathcal{S}_i) = k_{Ai}(0) \exp (a_{2i} \mathcal{S}_i^2), \qquad i = 1, 2.
$$

Molecular orientation scalar order parameter

$$
\mathcal{S} \equiv \sqrt{\frac{3}{2} \left(\mathbf{S} : \mathbf{S} \right)} \qquad \mathbf{S} = \frac{1}{3} \cdot \text{diag} \left(S_{rr}, -\left(S_{rr} + S_{xx} \right), \, S_{xx} \right),
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$$

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$$
\Lambda_{(1)} = \frac{\partial \Lambda}{\partial t} + \mathbf{v} \cdot \nabla \Lambda - \left(\nabla \mathbf{v}^T \cdot \Lambda + \Lambda \cdot \nabla \mathbf{v}\right)
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$$

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where subscript (1) denote UCTD operator

$$
\Lambda_{(1)} = \frac{\partial \Lambda}{\partial t} + \mathbf{v} \cdot \nabla \Lambda - \left(\nabla \mathbf{v}^T \cdot \Lambda + \Lambda \cdot \nabla \mathbf{v}\right)
$$

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Kinematic, dynamic and thermal boundary conditions are required:

- Initial conditions $(t = 0)$
- Die exit conditions $(x = 0)$
- Take–up point conditions $(x=L)$
- **Conditions on free surfaces** of hollow compound fiber $(r = R_1(x), r = R(x)$ and $r = R_2(x)$

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 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right\}$, $\left\{ \begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right\}$, $\left\{ \begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right\}$

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Non–dimensionalize

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Non–dimensional variables

$$
\hat{t} = \frac{t}{(L/u_0)} \qquad \hat{r} = \frac{r}{R_0} \qquad \hat{x} = \frac{x}{L} \qquad \Rightarrow \qquad \epsilon = \frac{R_0}{L}
$$
\n
$$
\hat{u} = \frac{u}{u_0} \qquad \hat{v} = \frac{v}{(u_0 \epsilon)} \qquad \hat{p} = \frac{p}{(\mu_0 u_0/L)} \qquad \hat{T} = \frac{T}{T_0}
$$
\n
$$
\hat{\rho} = \frac{\rho}{\rho_0} \qquad \hat{C} = \frac{C}{C_0} \qquad \hat{\mu} = \frac{\mu}{\mu_0} \qquad \hat{K} = \frac{K}{K_0}
$$

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 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right.$

Non–dimensional numbers

$$
Re = \frac{\rho_0 u_0 R_0}{\mu_0}, \quad Fr = \frac{u_0^2}{g R_0}, \quad Ca = \frac{\mu_0 u_0}{\sigma}.
$$

 $Pr = \frac{\mu_0 C_0}{K_0}, \quad Pe = Re Pr, \quad Bi = \frac{h R_0}{K_0}$

Non–dimensionalize

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Non–dimensional variables

$$
\begin{aligned}\n\hat{t} &= \frac{t}{(L/u_0)} & \hat{r} &= \frac{r}{R_0} & \hat{x} &= \frac{x}{L} & \Rightarrow & \epsilon &= \frac{R_0}{L} \\
\hat{u} &= \frac{u}{u_0} & \hat{v} &= \frac{v}{(u_0 \epsilon)} & \hat{p} &= \frac{p}{(\mu_0 u_0/L)} & \hat{T} &= \frac{T}{T_0} \\
\hat{\rho} &= \frac{\rho}{\rho_0} & \hat{C} &= \frac{C}{C_0} & \hat{\mu} &= \frac{\mu}{\mu_0} & \hat{K} &= \frac{K}{K_0}\n\end{aligned}
$$

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 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right.$

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• Asymptotic method using the fiber slenderness, $\epsilon \ll 1$, as perturbation parameter

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 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right.$

$$
\Psi_i = \Psi_{i,0} + \epsilon^2 \Psi_{i,2} + O(\epsilon^4) ,
$$

for the variables \hat{R}_i , \hat{u}_i , \hat{v}_i , \hat{p}_i and \hat{T}_i where $i=1,2.$

• Flow regime steady
$$
\left(\frac{\partial}{\partial \hat{t}}=0\right)
$$
 jets and

$$
Re = \epsilon \bar{R}, \qquad Fr = \frac{\bar{F}}{\epsilon}, \qquad Ca = \frac{\bar{C}}{\epsilon},
$$

$$
Pe = \epsilon \bar{P}, \qquad Bi = \epsilon^2 \bar{B}
$$

where $\overline{\Upsilon} = O(1)$.

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$$
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Asymptotic one–dimensional mass conservation equation

$$
\mathcal{A}_1 \mathcal{B} = V_1,
$$

$$
\mathcal{A}_2 \mathcal{B} = V_2,
$$

$$
\frac{d}{d\hat{x}} \left(\frac{\mathcal{R}_0^2}{2} \mathcal{B} \right) = \mathcal{C} (\hat{x})
$$

where

$$
\mathcal{A}_1=\frac{\mathcal{R}_0^2-\mathcal{R}_1^2}{2},\qquad \mathcal{A}_2=\frac{\mathcal{R}_2^2-\mathcal{R}_0^2}{2},
$$

and

$$
\mathcal{C}\left(\hat{x}\right) = \left(\frac{1}{2\bar{C}}\right) \frac{\left(\frac{\sigma_1}{\sigma}\right)\frac{1}{\mathcal{R}_1} + \frac{1}{\mathcal{R}_0} + \left(\frac{\sigma_2}{\sigma}\right)\frac{1}{\mathcal{R}_2}}{<\hat{\mu}_{e1,0} > \left(\frac{1}{\mathcal{R}_0^2} - \frac{1}{\mathcal{R}_1^2}\right) + <\hat{\mu}_{e2,0} > \left(\frac{1}{\mathcal{R}_2^2} - \frac{1}{\mathcal{R}_0^2}\right)},
$$

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One–dimensional equations of the 2D model

Asymptotic one–dimensional axial momentum equation

$$
(\hat{\rho}_1 V_1 + \hat{\rho}_2 V_2) \bar{R} \frac{d\mathcal{B}}{d\hat{x}} = (\hat{\rho}_1 \mathcal{A}_1 + \hat{\rho}_2 \mathcal{A}_2) \frac{\bar{R}}{\bar{F}}
$$

$$
+ \frac{d}{d\hat{x}} \left(3 \left(\langle \hat{\mu}_{e1,0} \rangle \mathcal{A}_1 + \langle \hat{\mu}_{e2,0} \rangle \mathcal{A}_2 \right) \frac{d\mathcal{B}}{d\hat{x}} \right)
$$

$$
+ 2 \mathcal{C}(\hat{x}) \left(-\frac{\langle \hat{\mu}_{e1,0} \rangle}{\mathcal{R}_1} \frac{d\mathcal{R}_1}{d\hat{x}} + \frac{\langle \hat{\mu}_{e1,0} \rangle - \langle \hat{\mu}_{e2,0} \rangle}{\mathcal{R}_0} \frac{d\mathcal{R}_0}{d\hat{x}} + \frac{\langle \hat{\mu}_{e2,0} \rangle}{\mathcal{R}_2} \frac{d\mathcal{R}_2}{d\hat{x}} \right)
$$

$$
- \left(\mathcal{A}_1 \frac{d\mathcal{D}_1}{d\hat{x}} + \mathcal{A}_2 \frac{d\mathcal{D}_2}{d\hat{x}} \right),
$$

where

$$
\mathcal{D}_1 = -\langle \hat{\mu}_{e1,0} \rangle \frac{2\mathcal{C}\left(\hat{x}\right)}{\mathcal{R}_1^2} - \frac{1}{\bar{C}} \left(\frac{\sigma_1}{\sigma}\right) \frac{1}{\mathcal{R}_1},
$$

$$
\mathcal{D}_2 = -\langle \hat{\mu}_{e2,0} \rangle \frac{2\mathcal{C}\left(\hat{x}\right)}{\mathcal{R}_2^2} + \frac{1}{\bar{C}} \left(\frac{\sigma_2}{\sigma}\right) \frac{1}{\mathcal{R}_2}.
$$

• Incompressibility condition

$$
\mathcal{V}(\hat{r}, \hat{x}) = \frac{\mathcal{C}\left(\hat{x}\right)}{\hat{r}} - \frac{\hat{r}}{2}\frac{d\mathcal{B}}{d\hat{x}}
$$

 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right.$ 目 Ω 13 / 27

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$$

$$
+ \frac{d}{d\hat{x}} \left(3 \left(\langle \hat{\mu}_{e1,0} \rangle \mathcal{A}_1 + \langle \hat{\mu}_{e2,0} \rangle \mathcal{A}_2 \right) \frac{d\mathcal{B}}{d\hat{x}} \right)
$$

$$
+ 2 \mathcal{C}(\hat{x}) \left(-\frac{\langle \hat{\mu}_{e1,0} \rangle}{\mathcal{R}_1} \frac{d\mathcal{R}_1}{d\hat{x}} + \frac{\langle \hat{\mu}_{e1,0} \rangle - \langle \hat{\mu}_{e2,0} \rangle}{\mathcal{R}_0} \frac{d\mathcal{R}_0}{d\hat{x}} + \frac{\langle \hat{\mu}_{e2,0} \rangle}{\mathcal{R}_2} \frac{d\mathcal{R}_2}{d\hat{x}} \right)
$$

$$
- \left(\mathcal{A}_1 \frac{d\mathcal{D}_1}{d\hat{x}} + \mathcal{A}_2 \frac{d\mathcal{D}_2}{d\hat{x}} \right),
$$

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where

$$
\mathcal{D}_1 = -\langle \hat{\mu}_{e1,0} \rangle \frac{2\mathcal{C}\left(\hat{x}\right)}{\mathcal{R}_1^2} - \frac{1}{\bar{C}} \left(\frac{\sigma_1}{\sigma}\right) \frac{1}{\mathcal{R}_1},
$$

$$
\mathcal{D}_2 = -\langle \hat{\mu}_{e2,0} \rangle \frac{2\mathcal{C}\left(\hat{x}\right)}{\mathcal{R}_2^2} + \frac{1}{\bar{C}} \left(\frac{\sigma_2}{\sigma}\right) \frac{1}{\mathcal{R}_2}.
$$

 \hat{r} dB 2 $d\hat{x}$,

• Incompressibility condition

$$
\mathcal{V}(\hat{r},\hat{x})=\frac{\mathcal{C}\left(\hat{x}\right)}{\hat{r}}-
$$

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Two–dimensional equations of the 2D model

Two–dimensional energy equation

$$
\mathcal{B}\frac{\partial \hat{T}_1}{\partial \hat{x}} + \left(\frac{\mathcal{C}\left(\hat{x}\right)}{\hat{r}} - \frac{\hat{r}}{2}\frac{d\mathcal{B}}{d\hat{x}}\right)\frac{\partial \hat{T}_1}{\partial \hat{r}} = \frac{1}{\bar{P}_1}\frac{1}{\hat{r}}\frac{\partial}{\partial \hat{r}}\left(\hat{r}\frac{\partial \hat{T}_1}{\partial \hat{r}}\right) \qquad \mathcal{R}_1 \leq \hat{r} \leq \mathcal{R}_0,
$$

$$
\hat{T}_1(\hat{r}, 0) = \tilde{T}_1(\hat{r}),
$$

$$
-\hat{K}_1 \frac{\partial \hat{T}_1}{\partial \hat{r}} (\mathcal{R}_1, \hat{x}) = 0,
$$

$$
\hat{T}_1 (\mathcal{R}_0, \hat{x}) = \hat{T}_2 (\mathcal{R}_0, \hat{x})
$$

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$$
\mathcal{B}\frac{\partial \hat{T}_2}{\partial \hat{x}} + \left(\frac{\mathcal{C}(\hat{x})}{\hat{r}} - \frac{\hat{r}}{2}\frac{d\mathcal{B}}{d\hat{x}}\right)\frac{\partial \hat{T}_2}{\partial \hat{r}} = \frac{1}{\bar{P}_2}\frac{1}{\hat{r}}\frac{\partial}{\partial \hat{r}}\left(\hat{r}\frac{\partial \hat{T}_2}{\partial \hat{r}}\right) \qquad \mathcal{R}_0 \leq \hat{r} \leq \mathcal{R}_2,
$$

$$
\hat{T}_2(\hat{r}, 0) = \tilde{T}_2(\hat{r}),
$$

\n
$$
-\hat{K}_2 \frac{\partial \hat{T}_2}{\partial \hat{r}}(\mathcal{R}_2, \hat{x}) = \bar{B} \hat{h}_2 \left(\hat{T}_2(\mathcal{R}_2, \hat{x}) - \hat{T}_{2,\infty} \right),
$$

\n
$$
-\hat{K}_1 \frac{\partial \hat{T}_1}{\partial \hat{r}}(\mathcal{R}_0, \hat{x}) = -\hat{K}_2 \frac{\partial \hat{T}_2}{\partial \hat{r}}(\mathcal{R}_0, \hat{x})
$$

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Two–dimensional degree of crystallinity equation

$$
\mathcal{B}\frac{\partial Y_i}{\partial \hat{x}} + \left(\frac{\mathcal{C}\left(\hat{x}\right)}{\hat{r}} - \frac{\hat{r}}{2}\frac{d\mathcal{B}}{d\hat{x}}\right)\frac{\partial Y_i}{\partial \hat{r}} = k_{Ai}(0)\exp\left(a_{2i}\mathcal{S}_i^2\right)\left(Y_{\infty,i} - Y_i\right), \qquad i = 1, 2,
$$

$$
Y_i(\hat{r}, 0) = \tilde{Y}_i(\hat{r}), \quad i = 1, 2,
$$

• Effective dynamic viscosity

$$
\hat{\mu}_{ei,0}(\hat{r},\hat{x}) = \hat{G}_i \exp\left(\hat{E}_i \left(1 - \hat{T}_i\right) + \beta_i \left(\frac{Y_i}{Y_{\infty,i}}\right)^{n_i}\right) + \frac{2}{3}\alpha_i \hat{\lambda}_i \mathcal{S}_i^2 \qquad i = 1, 2.
$$

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 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right. \times \left\{ \begin{array}{ccc} \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 \end{array} \right.$

Cross-sectionally averaged effective dynamic viscosity

$$
\langle \hat{\mu}_{e1,0} \rangle (\hat{x}) = \int_{\mathcal{R}_1}^{\mathcal{R}_0} \hat{\mu}_{e1,0}(\hat{r}, \hat{x}) \,\hat{r} \,d\hat{r} / \mathcal{A}_1,
$$

$$
\langle \hat{\mu}_{e2,0} \rangle (\hat{x}) = \int_{\mathcal{R}_0}^{\mathcal{R}_2} \hat{\mu}_{e2,0}(\hat{r}, \hat{x}) \,\hat{r} \,d\hat{r} / \mathcal{A}_2.
$$

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$$

Cross-sectionally averaged effective dynamic viscosity

$$
\langle \hat{\mu}_{e1,0} \rangle (\hat{x}) = \int_{\mathcal{R}_1}^{\mathcal{R}_0} \hat{\mu}_{e1,0}(\hat{r}, \hat{x}) \hat{r} d\hat{r} / A_1,
$$

$$
\langle \hat{\mu}_{e2,0} \rangle (\hat{x}) = \int_{\mathcal{R}_0}^{\mathcal{R}_2} \hat{\mu}_{e2,0}(\hat{r}, \hat{x}) \hat{r} d\hat{r} / A_2.
$$

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Two–dimensional equations for the molecular orientation tensor components

$$
\mathcal{B}\frac{\partial S_{irr}}{\partial \hat{x}} + \left(\frac{\mathcal{C}\left(\hat{x}\right)}{\hat{r}} - \frac{\hat{r}}{2}\frac{d\mathcal{B}}{d\hat{x}}\right)\frac{\partial S_{irr}}{\partial \hat{r}} = \left(1 - S_{irr}\right)\left(1 + S_{ixx}\right)\frac{d\mathcal{B}}{d\hat{x}}
$$

$$
-\frac{\phi_i}{\hat{\lambda}_i}\left\{S_{irr} + \frac{N_i}{3}\left[\left(S_{irr} - 1\right)\left(S_{irr} - O_{is}\right)\right]\right\}, \qquad i = 1, 2,
$$

$$
\mathcal{B}\frac{\partial S_{irr}}{\partial \hat{x}} + \left(\frac{\mathcal{C}\left(\hat{x}\right)}{\hat{r}} - \frac{\hat{r}}{2}\frac{d\mathcal{B}}{d\hat{x}}\right)\frac{\partial S_{irr}}{\partial \hat{r}} = \left(1 + S_{ixx}\right)\left(2 - S_{ixx}\right)\frac{d\mathcal{B}}{d\hat{x}}
$$

$$
-\frac{\phi_i}{\hat{\lambda}_i}\left\{S_{ixx} - \frac{N_i}{3}\left[\left(S_{ixx} + 1\right)\left(S_{ixx} - O_{is}\right)\right]\right\}, \qquad i = 1, 2,
$$

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$$
O_{i s}(\hat{r}, \hat{x}) = \frac{2}{3} \left(S_{irr}^2 + S_{ixx}^2 - S_{irr} S_{ixx} \right).
$$

$$
S_{irr}(\hat{r}, 0) = -\tilde{S}_i(\hat{r}),
$$

$$
S_{i\,xx}(\hat{r}, 0) = 2\tilde{S}_i(\hat{r}).
$$

Mapping: 2D model

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 $(\hat{r}, \hat{x}) \mapsto (\xi, \eta)$ maps $\Omega_{\hat{r}\hat{x}} = \{[\mathcal{R}_1(\hat{x}), \mathcal{R}_2(\hat{x})] \times [0, 1]\}$ into a rectangular domain $\Omega_{\epsilon n} = \{ [0, 1] \times [0, 1] \}$

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Two–dimensional energy equation

$$
\frac{\partial \hat{T}_1}{\partial \eta} = \frac{1}{2\,\left(V_1 + V_2\right)} \frac{4}{\bar{P}_1} \frac{\partial}{\partial \xi} \left(\left(\xi + \frac{\mathcal{R}_1^2}{\mathcal{R}_2^2 - \mathcal{R}_1^2}\right) \frac{\partial \hat{T}_1}{\partial \xi} \right) \qquad 0 \le \xi \le \frac{V_1}{V_1 + V_2},
$$

$$
\hat{T}_1(\xi, 0) = \tilde{T}_1(\xi),
$$

$$
-\hat{K}_1 \frac{\partial \hat{T}_1}{\partial \xi}(0, \eta) = 0,
$$

$$
\hat{T}_1 \left(\frac{V_1}{V_1 + V_2}, \eta \right) = \hat{T}_2 \left(\frac{V_1}{V_1 + V_2}, \eta \right)
$$

$$
\frac{\partial \hat{T}_2}{\partial \eta} = \frac{1}{2\,\left(V_1 + V_2\right)}\, \frac{4}{\bar{P}_2}\, \frac{\partial}{\partial \xi}\left(\left(\xi + \frac{\mathcal{R}_1^2}{\mathcal{R}_2^2 - \mathcal{R}_1^2}\right)\frac{\partial \hat{T}_2}{\partial \xi}\right) \qquad \frac{V_1}{V_1 + V_2} \leq \xi \leq 1,
$$

$$
\hat{T}_2(\xi, 0) = \tilde{T}_2(\xi),
$$
\n
$$
-\hat{K}_2 \frac{\partial \hat{T}_2}{\partial \xi}(1, \eta) = \frac{\mathcal{R}_2^2 - \mathcal{R}_1^2}{2 \mathcal{R}_2} \bar{B} \hat{h}_2 \left(\hat{T}_2(1, \eta) - \hat{T}_{2, \infty} \right),
$$
\n
$$
-\hat{K}_1 \frac{\partial \hat{T}_1}{\partial \xi} \left(\frac{V_1}{V_1 + V_2}, \eta \right) = -\hat{K}_2 \frac{\partial \hat{T}_2}{\partial \xi} \left(\frac{V_1}{V_1 + V_2}, \eta \right)
$$
\n
$$
\iff \langle \xi \rangle \iff \langle
$$

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$$

$$
Y_i(\xi, 0) = \tilde{Y}_i(\xi), \qquad i = 1, 2,
$$

• Effective dynamic viscosity

$$
\hat{\mu}_{ei,0}(\xi,\,\eta) = \hat{G}_i \, \exp\left(\hat{E}_i \left(1-\hat{T}_i\right) + \beta_i \left(\frac{Y_i}{Y_{\infty,i}}\right)^{n_i}\right) + \frac{2}{3} \, \alpha_i \, \hat{\lambda}_i \mathcal{S}_i^2 \qquad i = 1,2.
$$

Cross-sectionally averaged effective dynamic viscosity

$$
\langle \hat{\mu}_{e1,0} \rangle (\eta) = \frac{V_1 + V_2}{V_1} \int_0^{\frac{V_1}{V_1 + V_2}} \hat{\mu}_{e1,0}(\xi, \eta) d\xi,
$$

$$
\langle \hat{\mu}_{e2,0} \rangle (\eta) = \frac{V_1 + V_2}{V_2} \int_{\frac{V_1}{V_1 + V_2}}^1 \hat{\mu}_{e2,0}(\xi, \eta) d\xi.
$$

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-\frac{\phi_i}{\hat{\lambda}_i}\left\{S_{irr} + \frac{N_i}{3}\left[\left(S_{irr} - 1\right)\left(S_{irr} - O_{is}\right)\right]\right\}, \qquad i = 1, 2,
$$

$$
\mathcal{B}\frac{\partial S_{i\,xx}}{\partial \eta} = (1 + S_{i\,xx})\left(2 - S_{i\,xx}\right)\frac{d\mathcal{B}}{d\eta}
$$

$$
-\frac{\phi_i}{\hat{\lambda}_i}\left\{S_{i\,xx} - \frac{N_i}{3}\left[\left(S_{i\,xx} + 1\right)\left(S_{i\,xx} - O_{i\,s}\right)\right]\right\}, \qquad i = 1, 2,
$$

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O_{i s}(\xi, \eta) = \frac{2}{3} \left(S_{irr}^2 + S_{ixx}^2 - S_{irr} S_{ixx} \right).
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 $(- \cdot -)$

 $G_2 = 1$ (-), $G_2 = 0.01$ (--) and $G_2 = 100$

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Effect of the cladding's viscosity parameters

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 $E_2 = 100$ (-), $E_2 = 50$ (--) and $E_2 = 10$ $(- - -)$

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1D model vs 2D model

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1D (-) and 2D ($- \cdot -$)

 $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array} \right\}$, $\left\{ \begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right\}$, $\left\{ \begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right\}$ E QQQ 24 / 27

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Contributions of the present work:

- Development of a quasi–two–dimensional model for semi–crystalline hollow compound fibers with modified Newtonian rheology.
- **2** 1D model (asymptotic analysis for $\epsilon << 1$) for \mathcal{R}_i and \mathcal{B} and $2\mathsf{D}$ equations for \hat{T}_i , \mathcal{S}_i and $Y_i.$
- 3 Determination of the two–dimensional fields of temperature, order parameter for molecular orientation and degree of crystallinity for hollow compound fibers.
- **4** Integro–differential model highly dependent on E_2 and G_2 .
- 5 Find substantial temperature non–uniformities (may affect the degree of crystallization and have great effects on the mechanical, optical,... properties of hollow compound fibers) in the radial direction.

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