Weak solutions to some problems in thermodynamics of fluids

Eduard Feireisl

Institute of Mathematics, Academy of Sciences of the Czech Republic, Prague

with E.Chiodaroli, O.Kreml, A.Novotný, Y.Sun

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Basic field equations

Mass conservation

$$\partial_t \varrho + \mathrm{div}_x(\varrho \mathbf{u}) = 0$$

Momentum balance

$$\partial_t(\varrho \mathbf{u}) + \mathrm{div}_x(\varrho \mathbf{u} \otimes \mathbf{u}) + \nabla_x p(\varrho, \vartheta) = \mathrm{div}_x \mathbb{S}(\nabla_x \mathbf{u})$$

Internal energy balance

$$\partial_t(\varrho e(\varrho, \vartheta)) + \mathrm{div}_x(\varrho e(\varrho, \vartheta)\mathbf{u}) + \mathrm{div}_x \mathbf{q} = \mathbb{S}(\nabla_x \mathbf{u}) : \nabla_x \mathbf{u} - p(\varrho, \vartheta)\mathrm{div}_x \mathbf{u}$$

Constitutive relations

Newton's law

$$\mathbb{S}(\nabla_x \mathbf{u}) = \mu \left(\nabla_x \mathbf{u} + \nabla_x^t \mathbf{u} - \frac{2}{3} \mathrm{div}_x \mathbf{u} \mathbb{I} \right) + \eta \mathrm{div}_x \mathbf{u} \mathbb{I}$$

Fourier's law

$$\mathbf{q} = -\kappa \nabla_x \vartheta$$

Gibbs' equation

$$\vartheta Ds(\varrho, \vartheta) = De(\varrho, \vartheta) + p(\varrho, \vartheta) D \left(\frac{1}{\varrho} \right)$$

Thermodynamics stability

$$\frac{\partial p(\varrho, \vartheta)}{\partial \varrho} > 0, \ \frac{\partial e(\varrho, \vartheta)}{\partial \vartheta} > 0$$

Local well posedness

Initial data

$$\varrho(0, \cdot) = \varrho_0 > 0, \ \vartheta(0, \cdot) = \vartheta_0 > 0, \ \mathbf{u}(0, \cdot) = \mathbf{u}_0$$

Regularity

$$\varrho, \ \vartheta, \ \mathbf{u} \in W^{m,2}, \ m \geq 3$$

Local existence for viscous fluids - Navier-Stokes-Fourier system

A. Valli, W.Zajaczkowski [1982] - local existence for large data,
A.Matsumura, T.Nishida [1980,1983] - global existence for small data

Local existence for ideal (inviscid) fluids - Euler-Fourier system

T. Alazard [2006], Serre [2008] - local existence for large data

Several "equivalent" forms of energy balance

Internal energy balance

$$\partial_t(\varrho e) + \mathrm{div}_x(\varrho e\mathbf{u}) + \mathrm{div}_x\mathbf{q} = \boxed{\mathbb{S}(\nabla_x\mathbf{u}):\nabla_x\mathbf{u}} - \boxed{p\,\mathrm{div}_x\mathbf{u}}$$

Entropy production

$$\partial_t(\varrho s) + \mathrm{div}_x(\varrho s\mathbf{u}) + \mathrm{div}_x\left(\frac{\mathbf{q}}{\vartheta}\right) \boxed{=} \frac{1}{\vartheta}\left(\boxed{\mathbb{S}(\nabla_x\mathbf{u}):\nabla_x\mathbf{u}} - \frac{\mathbf{q}\cdot\nabla_x\vartheta}{\vartheta}\right)$$

Total energy balance

$$\partial_t\left(\frac{1}{2}\varrho|\mathbf{u}|^2 + \varrho e\right) + \mathrm{div}_x\left[\left(\frac{1}{2}\varrho|\mathbf{u}|^2 + \varrho e\right)\mathbf{u} + p\mathbf{u}\right] + \mathrm{div}_x\mathbf{q}$$

$$= -\boxed{\mathrm{div}_x(\mathbb{S}(\nabla_x\mathbf{u})\cdot\mathbf{u})}$$

Weak formulation

Second law - entropy inequality

$$\partial_t(\varrho s) + \text{div}_x(\varrho s \mathbf{u}) + \text{div}_x\left(\frac{\mathbf{q}}{\vartheta}\right) \geq \frac{1}{\vartheta}\left(\mathbb{S}(\nabla_x \mathbf{u}) : \nabla_x \mathbf{u} - \frac{\mathbf{q} \cdot \nabla_x \vartheta}{\vartheta}\right)$$

First law - total energy balance

$$\partial_t \int \left(\frac{1}{2}\varrho|\mathbf{u}|^2 + \varrho e\right) \, \mathrm{d}x = 0$$

Relative entropy (energy)

Relative entropy functional

$$\mathcal{E}\left(\varrho, \vartheta, \mathbf{u} \ \middle| \ r, \Theta, \mathbf{U}\right)$$

$$= \int_{\Omega} \left(\frac{1}{2} \varrho |\mathbf{u} - \mathbf{U}|^2 + H_{\Theta}(\varrho, \vartheta) - \frac{\partial H_{\Theta}(r, \Theta)}{\partial \varrho}(\varrho - r) - H_{\Theta}(r, \Theta) \right) \ \mathrm{d}x$$

Ballistic free energy

$$H_{\Theta}(\varrho, \vartheta) = \varrho \Big(e(\varrho, \vartheta) - \Theta s(\varrho, \vartheta) \Big)$$

Coercivity of the ballistic free energy

$\varrho \mapsto H_{\Theta}(\varrho, \Theta)$ strictly convex

$\vartheta \mapsto H_{\Theta}(\varrho, \vartheta)$ decreasing for $\vartheta < \Theta$ and increasing for $\vartheta > \Theta$

Dissipative solutions

Relative entropy inequality

$$\left[\mathcal{E}\left(\varrho, \vartheta, \mathbf{u} \middle| r, \Theta, \mathbf{U}\right) \right]_{t=0}^{\tau}$$

$$+ \int_0^\tau \int_\Omega \frac{\Theta}{\vartheta} \left(\mathbb{S}(\vartheta, \nabla_x \mathbf{u}) : \nabla_x \mathbf{u} - \frac{\mathbf{q}(\vartheta, \nabla_x \vartheta) \cdot \nabla_x \vartheta}{\vartheta} \right) \, \mathrm{d}x \, \mathrm{d}t$$

$$\leq \int_0^\tau \mathcal{R}(\varrho, \vartheta, \mathbf{u}, r, \Theta, \mathbf{U}) \, \mathrm{d}t$$

for any $r > 0$, $\Theta > 0$, $\mathbf{U}$ satisfying relevant boundary conditions

$$\boxed{\mathcal{R}(\varrho, \vartheta, \mathbf{u}, r, \Theta, \mathbf{U})}$$

$$= \int_{\Omega} \left(\varrho \Big(\partial_t \mathbf{U} + \mathbf{u} \cdot \nabla_x \mathbf{U} \Big) \cdot (\mathbf{U} - \mathbf{u}) + \mathbb{S}(\vartheta, \nabla_x \mathbf{u}) : \nabla_x \mathbf{U} \right) \, \mathrm{d}x$$

$$+ \int_{\Omega} \left[\Big(p(r, \Theta) - p(\varrho, \vartheta) \Big) \mathrm{div} \mathbf{U} + \frac{\varrho}{r} (\mathbf{U} - \mathbf{u}) \cdot \nabla_x p(r, \Theta) \right] \, \mathrm{d}x$$

$$- \int_{\Omega} \left(\varrho \Big(s(\varrho, \vartheta) - s(r, \Theta) \Big) \partial_t \Theta + \varrho \Big(s(\varrho, \vartheta) - s(r, \Theta) \Big) \mathbf{u} \cdot \nabla_x \Theta \right.$$

$$\left. + \frac{\mathbf{q}(\vartheta, \nabla_x \vartheta)}{\vartheta} \cdot \nabla_x \Theta \right) \, \mathrm{d}x$$

$$+ \int_{\Omega} \frac{r - \varrho}{r} \Big(\partial_t p(r, \Theta) + \mathbf{U} \cdot \nabla_x p(r, \Theta) \Big) \, \mathrm{d}x$$

Weak solutions - summary

Global existence in the viscous case

Global-in-time weak dissipative solutions of the
Navier-Stokes-Fourier system exist for any finite energy initial
data (under some hypotheses imposed on constitutive relations)

Compatibility

Regular weak solutions are strong solutions

Weak-strong uniqueness

Weak and strong solutions emanating from the same (regular) initial
data coincide as long as the latter exists. The strong solutions are
unique in the class of weak solutions

Conditional regularity

Sufficient condition for regularity

Suppose that a dissipative weak solution to the Navier-Stokes-Fourier system emanating from regular initial data satisfies

$$\|\nabla_x \mathbf{u}\|_{L^\infty((0,T)\times\Omega)} < \infty.$$

Then the solution is regular in $(0, T)$.

Euler-Fourier system

Mass conservation

$$\partial_t \varrho + \mathrm{div}_x(\varrho \mathbf{u}) = 0$$

Momentum balance

$$\partial_t(\varrho \mathbf{u}) + \mathrm{div}_x(\varrho \mathbf{u} \otimes \mathbf{u}) + \nabla_x(\varrho \vartheta) = 0$$

Internal energy balance

$$\frac{3}{2}\Big[\partial_t(\varrho \vartheta) + \mathrm{div}_x(\varrho \vartheta \mathbf{u})\Big] - \Delta \vartheta = -\varrho \vartheta \mathrm{div}_x \mathbf{u}$$

Existence of weak solutions

Initial data

$$\varrho_0, \ \vartheta_0, \ \mathbf{u}_0 \in C^3, \ \varrho_0 > 0, \ \vartheta_0 > 0$$

Global existence

For any (smooth) initial data $\varrho_0, \ \vartheta_0, \ \mathbf{u}_0$ the Euler-Fourier system admits infinitely many weak solutions on a given time interval $(0, T)$

Regularity class

$$\varrho \in C^2, \ \partial_t \vartheta, \ \nabla_x^2 \vartheta \ \in L^p \text{ for any } 1 \leq p < \infty$$

$$\mathbf{u} \in C_{\mathrm{weak}}([0, T]; L^2) \cap L^\infty, \ \mathrm{div}_x \mathbf{u} \in C^1$$

Application of the convex integration method

Ansatz

$$\varrho \mathbf{u} = \mathbf{v} + \nabla_x \Psi, \ \mathrm{div}_x \mathbf{v} = 0$$

Equations

$$\partial_t \varrho + \Delta \Psi = 0$$

$$\partial_t \mathbf{v} + \mathrm{div}_x \left(\frac{(\mathbf{v} + \nabla_x \Psi) \otimes (\mathbf{v} + \nabla_x \Psi)}{\varrho} \right) + \nabla_x (\partial_t \Psi + \varrho \vartheta) = 0$$

$$\frac{3}{2} \left(\partial_t (\varrho \vartheta) + \mathrm{div}_x \Big(\vartheta (\mathbf{v} + \nabla_x \Psi) \Big) \right) - \Delta \vartheta = -\varrho \vartheta \mathrm{div}_x \left(\frac{\mathbf{v} + \nabla_x \Psi}{\varrho} \right)$$

"Energy"

$$e = \chi(t) - \frac{3}{2} \varrho \vartheta [\mathbf{v}]$$

Dissipative solutions to the Euler-Fourier system

Initial data

$$\varrho_0 \in C^2, \vartheta_0 \in C^2, \ \varrho_0 > 0, \ \vartheta_0 > 0$$

Infinitely many dissipative weak solutions

For any regular initial data ϱ_0, ϑ_0, there exists a velocity field $\mathbf{u}_0$ such that the Euler-Fourier problem admits infinitely many dissipative weak solutions in $(0, T)$

Maximal dissipation criterion?

Entropy production rate

$$\partial_t(\varrho s) + \mathrm{div}_x(\varrho s \mathbf{u}) + \mathrm{div}_x\left(\frac{\mathbf{q}}{\vartheta}\right) = \sigma$$

$$\sigma \boxed{\geq} \frac{1}{\vartheta}\left(\mathbb{S}(\nabla_x \mathbf{u}) : \nabla_x \mathbf{u} - \frac{\mathbf{q} \cdot \nabla_x \vartheta}{\vartheta}\right)$$

Criterion à la Dafermos 1974

Admissible solutions should "maximize" the entropy production rate σ