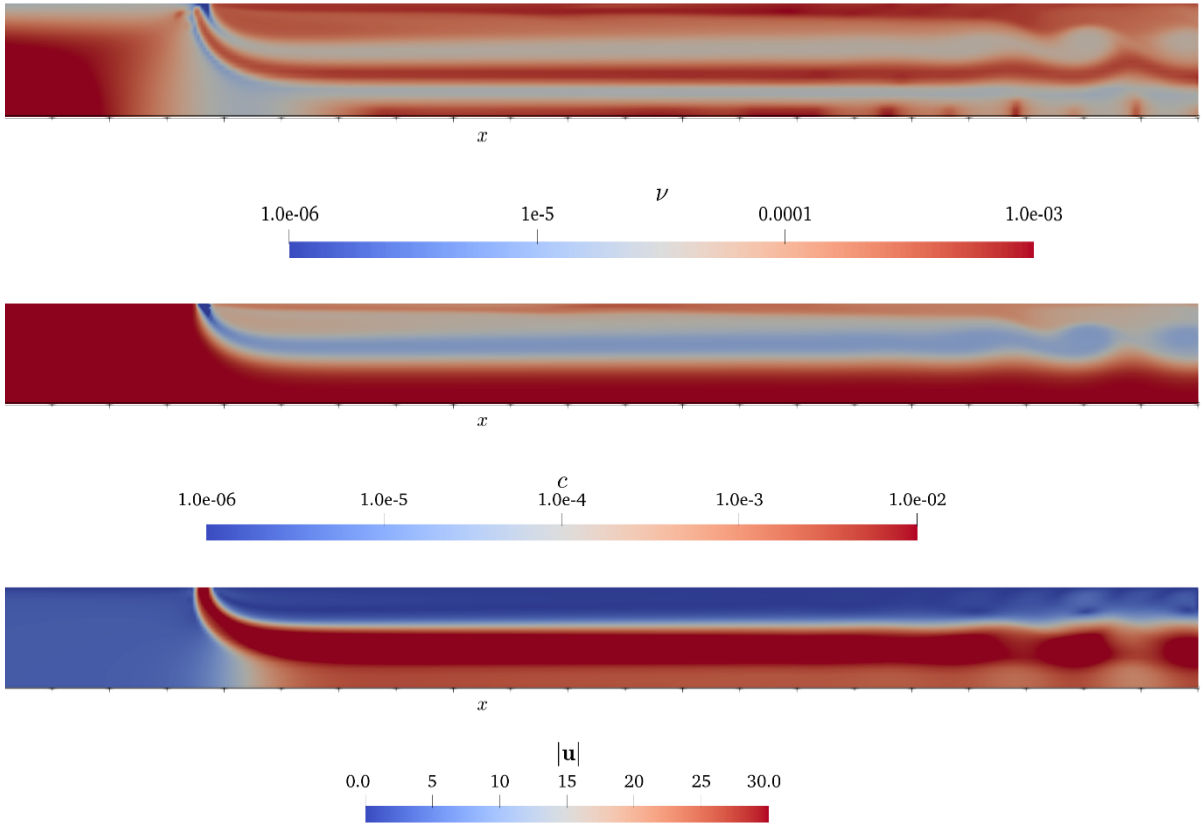
Advanced Viscosity Models in OpenFOAM

Implementation and Stability



Velocity, concentration, and viscosity field in pipe flow with water injection

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23 minutes speaking time

Viscosity Model Basics

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Non-Newtonian Fluids

Generalized Newtonian Fluid Models

- Power Law Model
- Carreau-Yasuda Model

Standard OpenFOAM
(e.g., OpenFOAM-6/src/transportModels/incompressible)

Linear Viscoelastic Fluid Models

- Maxwell Model
- Jeffreys Model

Nonlinear Viscoelastic Fluid Models

- Giesekus Model
- Phan-Thien & Tanner Model
- FENE-CR Model

Specialized OpenFOAM functionality
(e.g., foam-extend-foam-extend-4.0, fppimenta/rheoTool)

- Solve additional transport equation
- Need stabilization

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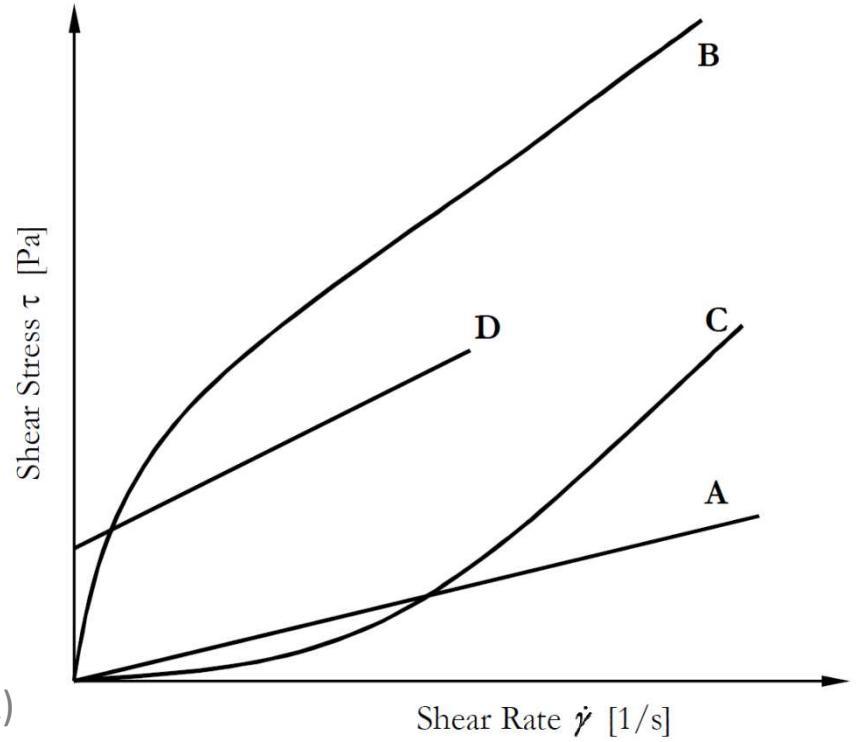
Standard OpenFOAM
(e.g., OpenFOAM-6/src/transportModels/incompressible)

A…Newtonian
B…shear thinning fluid ("pseudoplastic")
C…shear thickening fluid ("dilatant")
D…Bingham plastic



Viscosity Model Basics

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Standard OpenFOAM
(e.g., OpenFOAM-6/src/transportModels/incompressible)

$$D = \frac{1}{2} \cdot \left(\nabla \vec{u} + \nabla \vec{u}^{T} \right)$$

$$\dot{\gamma} = \sqrt{2 \cdot tr\left(D^2\right)}$$

Herschel-Bulkley (A+D)
(„yield stress fluids“)

$$\tau\left(\vec{x}\right) = \tau_0 + k\,\dot{\gamma}\left(\vec{x}\right)^n$$

$$\mu\left(\vec{x}\right) = \min\left[\mu_0, \frac{\tau\left(\vec{x}\right)}{\dot{\gamma}\left(\vec{x}\right)}\right]$$

Why Advanced Viscosity Models?

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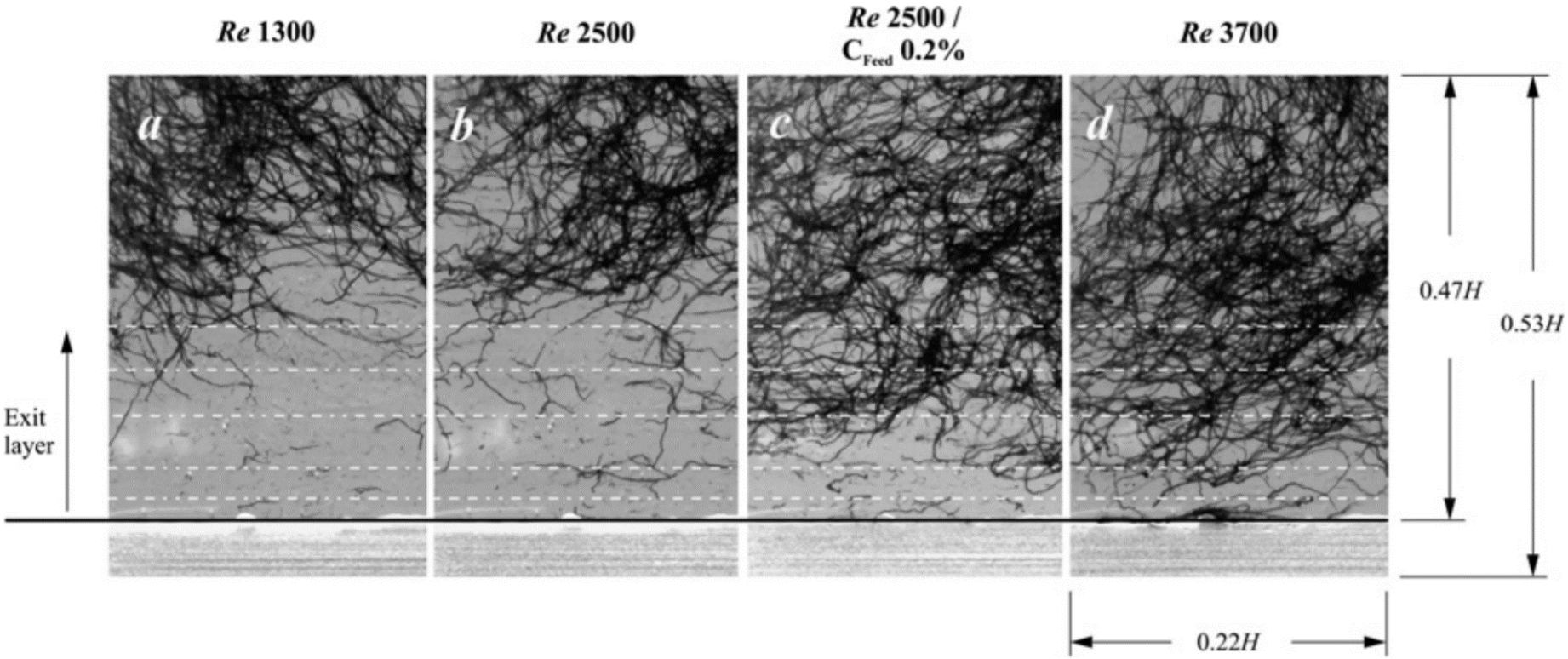
…because fluid viscosity is often a function of a **spatially-variable property** (e.g., the temperature, or the composition)



Redlinger-Pohn et al. (Chem. Eng. Res. Des. 126:54–66, 2017),
Schmid et al. (Nordic Pulp & Paper Research Journal 2019; 34(2): 182–199

Goal & Expected Results

…couple a simple scalar transport model with a **Herschel-Bulkley viscosity model**.

A **concentration and shear rate dependent** rheological model is available in OpenFOAM 5.x

$$\tau\left(\vec{x},c\right)=\tau_0\left(c\right)+k\left(c\right)\dot{\gamma}\left(\vec{x}\right)^{n(c)}$$

$$\mu\left(\vec{x},c\right)=\min\left[\mu_0,\frac{\tau\left(\vec{x},c\right)}{\dot{\gamma}\left(\vec{x}\right)}\right]$$

Prerequisite

…ensure **you know what you are doing**
(https://**wiki.openfoam.com**/Programming)

Phase 1: Add Scalar Transport Solver

…in controlDict, add:

```
scalarTransportSolver_1
{
    functionObjectLibs ("libfuncSolversIPPTFunctionObjects.so");
    type                scalarTransportIPPT;
    Schmidt             1e99;
    SchmidtTurb         0.7;
    schemesField        s;
    solutionField       s;
    field               "c";

    fvOptions
    {
    }
}
```

…a slightly „pimped“ solver

…add initial field for “c”, as well as modify fvSolution and fvSchemes

Phase 1: Add Scalar Transport Solver

…our “pimped” scalar transport solver does the following

```
//*****************************************
// Helper function to calculate local diffusivity
...scalarTransportIPPT::D(phi)
{
    return model.nu()/Schmidt_ + model.nut()/SchmidtTurb_
}

//*****************************************
// Calculate the diffusivity
volScalarField D(this->D(phi));

// Assembe Eqn & Solve
fvScalarMatrix sEqn
        (
            fvm::ddt(rho, s_)
          + fvm::div(phi, s_, divScheme)
          - fvm::laplacian(D, s_, laplacianScheme)
         ==
            fvOptions_(rho, s_)
        );
```

Phase 2: Implement viscosity model

…simply **copy-paste-rename** Herschel-Bulkley model from OpenFOAM src code

… in constructor add **ability to read name of concentration field** (you may want to read additional parameters if you like…)
…also add a bool to **avoid run before first time step**

```
Foam::viscosityModels::HerschelBulkleyIPPT::HerschelBulkleyIPPT
(
    const word& name,
    const dictionary& viscosityProperties,
    const volVectorField& U,
    const surfaceScalarField& phi
)
:
    viscosityModel(name, viscosityProperties, U, phi),
    hasBeenCalled_(false),
...
    concName_(HerschelBulkleyIPPTCoeffs_.lookupOrDefault<word>("concName", "C"))
{
}
```

Phase 2: Implement viscosity model

…implement (**your {possibly} secret**) rheological model. You might want to ensure (i) **correct limiting behavior**, (ii) **calculation of negative viscosities**.

```
if(hasBeenCalled_)
{
    const volScalarField& Conc_ = U_.mesh().lookupObject<volScalarField>(concName_);

    return
    (
        min
        (
        nu0_,
        (
          (0.123 * pow(Conc_,2) + 0.123 * Conc_)    //tau0_(Conc_)
          * dimensionedScalar ("oneStress", dimLength*dimLength/dimTime/dimTime, 1.0)

        +  (0.123 * Conc_ + 0.123)
          *dimensionedScalar ("oneVisc", dimLength*dimLength/dimTime, 1.0) //k_(Conc_)

        *  rtone
        *  pow(tone*sr(),
              0.123+(1.0-0.123)*exp(-Conc_ * 0.123)  //n_(Conc_)
            )
        )
       /(max(sr(), dimensionedScalar ("VSMALL", dimless/dimTime, VSMALL)))
        )
    );
}
```

Hint: …instead of “lookupObject” on could possibly find better alternatives (findObject, getObjectPtr…) [thanks to Mark Olesen for the hint]

Phase 3: Activate model

…after letting OpenFOAM know in which library file your viscosity model resides (in controlDict, add:

```
libs ("libUserViscosityIPPT.so");
```

),

you can simply activate in your transportProperties file:

```
transportModel  HerschelBulkleyIPPT;

HerschelBulkleyIPPTCoeffs
{
    concName    "c";
    k [0 2 -1 0 0 0 0]      0.06522;    //Only needed for first time step!
    n [0 0  0 0 0 0 0]      0.1124;     //Only needed for first time step!
    tau0 [0 2 -2 0 0 0 0]   0.1363;     //Only needed for first time step!
    nu0 [0 2 -1 0 0 0 0]    1e-3;
}
```

Adressing Stability Issues

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Goal & Expected Results

…auto-adjust time step depending on flow and fluid properties (i.e., impose **Courant and „viscosity number“ limitation**)

…ensure a **stable simulation (dynamically choose time step)**.

A functionObject is available that set the timestep based on a limiting „**viscosity number**“ (in addition to a predefined Courant number).

Prerequisite

…**again**, ensure **you know what you are doing** (https://wiki.openfoam.com/Programming)

Phase 1: Decide how to limit the time step

…the usual **Courant number-based limiter** should remain to be active

$$Co_{\max} = \frac{\Delta t}{\min\left(\Delta x / U\right)}$$

$$Co_{\max} = \frac{\Delta t}{\min\left(\Delta V / \left[0.5 \sum_{i \in faces} |\phi_i|\right]\right)}$$

…**in addition, a „viscosity number"-based limitation** should kick in in high viscosity regions

$$t^{*,visc} = \frac{\Delta t}{\min\left(\Delta x^2 / \nu_{eff}\right)}$$

Adressing Stability Issues

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Phase 2: Implementation as functionObject

…derived from class „fvMeshFunctionObject“, and similar to „setTimeStep“

…allows setting a single value for the time step (or $t^{*,visc}$) **or a table (change time step during start up of simulation)**

```
//- Time step function (single value or table: this is why it is
implemented like this)
autoPtr<Function1<scalar>> timeStepPtr_;
autoPtr<Function1<scalar>> viscDimLessTimePtr_;
```

…takes the **minimum of the Courant number-based time step**, a predefined **minimum time step, as well as the $t^{*,visc}$-based time step**

…uses relaxation to avoid rapid changes of time step

Adressing Stability Issues

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Phase 2: Implementation as functionObject

```
bool Foam::functionObjects::setTimeStepViscAutoFunctionObject::adjustTimeStep()
{
    if(!hasBeenExecuted_) return false;

    scalar targetTimeStep =  min(
                                timeStepPtr_().value(time_.timeOutputValue()),
                                min( minViscTime_*viscDimLessTimePtr_().value(time_.
                                timeOutputValue()),
                                time_.deltaT().value())
                            );

//    Info << "time step before adjustment:   " << currentTimeStep_ << endl;
//    Info << "target time step:              " << targetTimeStep << endl;
    currentTimeStep_ = currentTimeStep_*(1.0-relaxationTimeFactor_)
                     + relaxationTimeFactor_*targetTimeStep;
    const_cast<Time&>(time()).setDeltaT
    (
        currentTimeStep_,
        false
    );

    return true;
}
```

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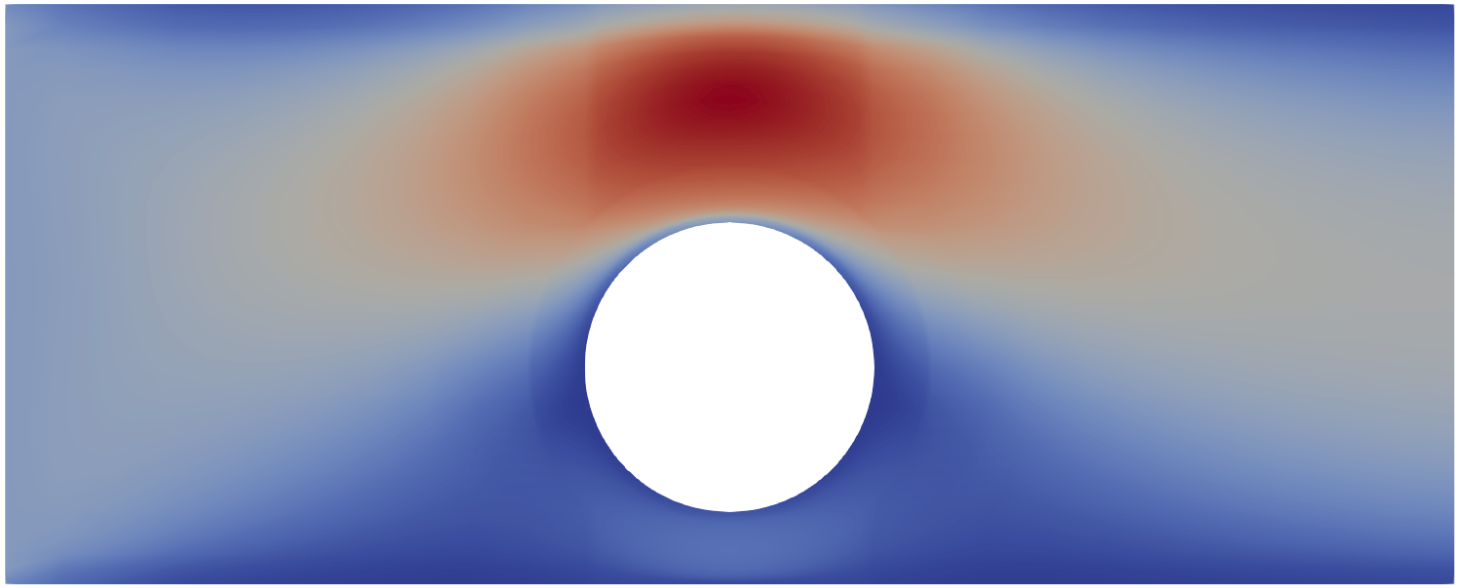
Case 1 - offsetCylinder

…steady-state flow of a power-law fluid („CrossPowerLaw“) with n=m=1, nu0 = 10, nuInf=0. 1



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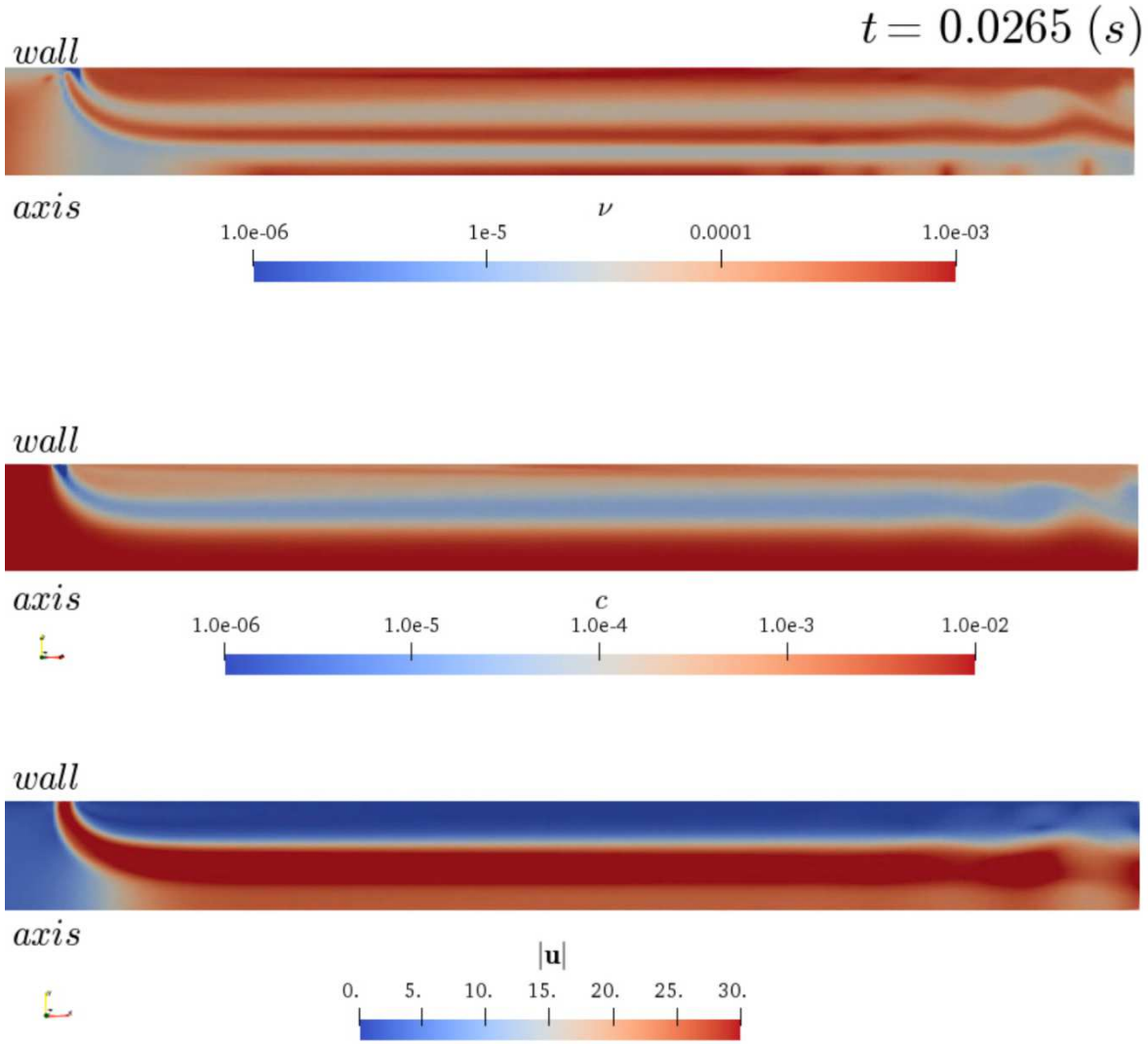
Case 2 - Pipe Flow with Wall Water Injection

…axisymmetric, plug flow inlet profile, radial water injection



Results for
U_{inj} = 30 [m/s]

Conclusions

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- No new solver - **pimpleFoam** is great!
- Use functionsObjects as long as there is no **complex back coupling**.
- Automatic time stepping control is easy to realize – use ‚**setTimeStep**‘ as a template
- https://**wiki.openfoam.com**/ViscousTimeStep Limitation_by_Stefan_Radl to **access files**

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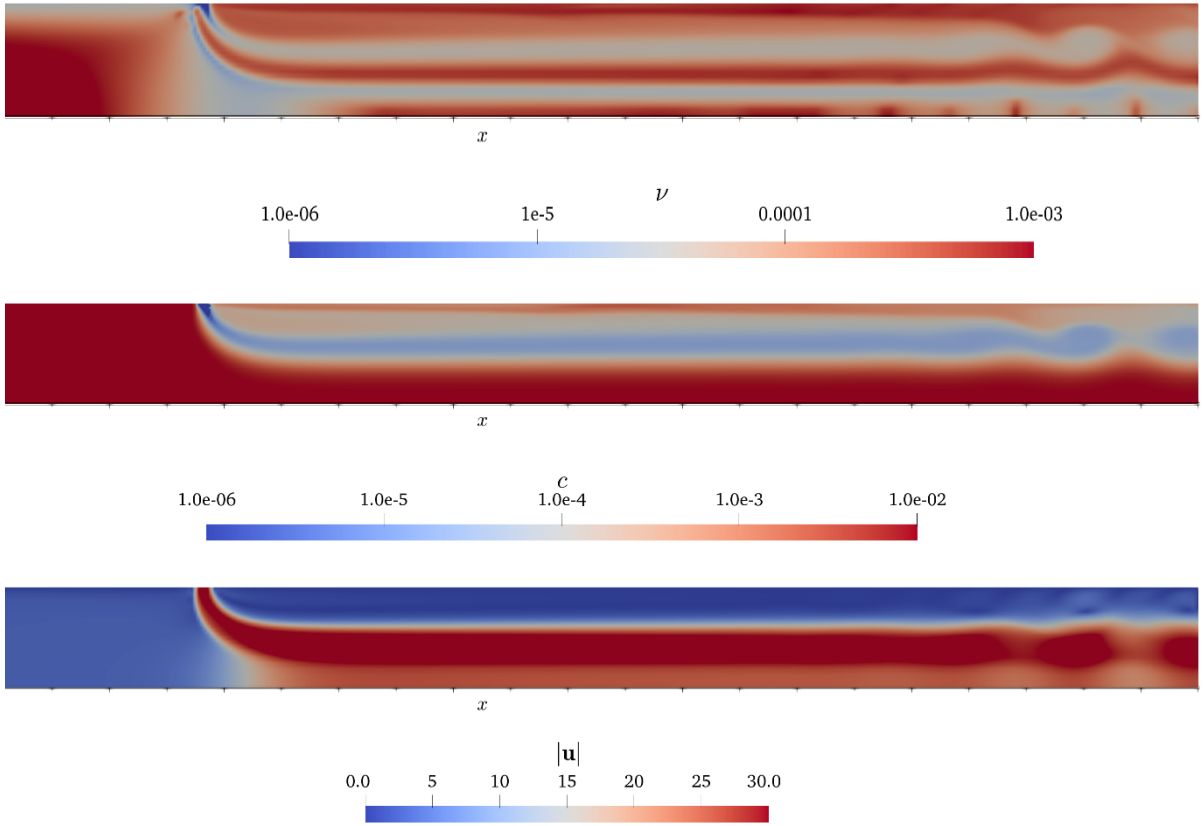

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