# Heat transfer in OpenFOAM

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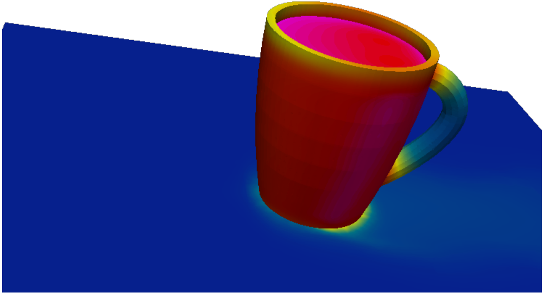

# Contents

## What is the aim of this training course?

- Understand principle mechanismn of heat transfer
- We will take a look a the principle mistakes for numerical calculation of heat transer
- Get to know OpenFOAM to solve common heat transfer problems
- Learn how to set up cases using OpenFOAM

What is the aim of this training course?

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- Let's do the dance!

## Which ways exist to transfer energy?

- Heat transfer due to convection
- Heat transfer due to conduction
- Heat transfer due to radiation

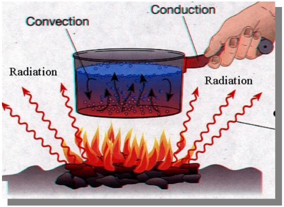


*Fig.: www.ploytechnichub.com*

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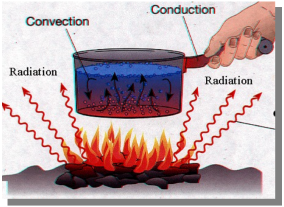


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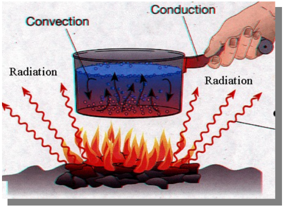


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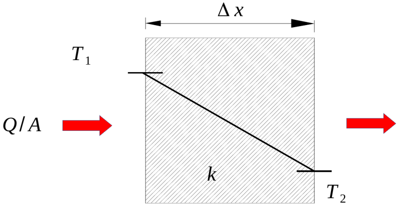
- If you think we are done ... **wrong!**
- **For numerical simulations of heat transfer problems a more detailed classification is required!**

## Heat conduction

- Heat transfer due to molecular motion and interaction
- Heat transfer through solids due to molecular vibration
- Fourier determined that $Q/A$ per unit area $W/m^2$ is proportional to the temperature gradient $dT/dx$

$$Q/A = -k\frac{\partial T}{\partial x} \qquad (1)$$



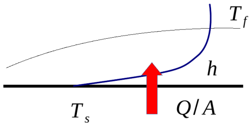
## Heat convection

- Convection heat transfer through gases and liquids from a solid boundary results from the fluid motion along the surface
- According to Newton law, the ratio of heat transfer is proportional of the temperature of the fluid and surface
- The constant of proportionality is called heat transfer coefficient $h$

$$Q/A = h(T_f - T_{sf}) \quad (2)$$

- $h$ is dependent on the fluid velocity, material properties, surface structure, ...

$$h = h(I, A, \mu, \rho, R_a, ...) \quad (3)$$



## Radiation

- Energy transport due to emission of electromagnetic waves or photons from a surface or volume coefficients
- Require not a medium, can occur in vacuum
- Heat transfer is proportional to the fourth power of the material temperature
- Proportionality constant is the Stefan Boltzmann constant

$$\sigma = 5.67 \times 10^{-8} W/m^2 K^4 \tag{4}$$

- Radiation heat transfer depends also on the material property, represented by the emissivity

$$Q/A = \epsilon \sigma T^4 \tag{5}$$

## Classification of heat transfer problems

- Which fluids / solids taken part in the process?

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## Classification of heat transfer problems

- Which fluids / solids taken part in the process?
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- Which kind of modeling for turbulent heat fluxes do we need?

## Classification of heat transfer problems

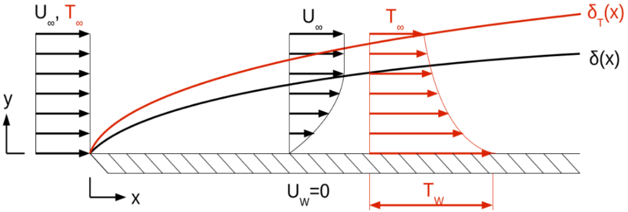
- Which fluids / solids taken part in the process?
- Which material properties do we expect?
- Do we have laminar or turbulent flow? Do we have a steady or unsteady problem? What is the Reynolds and Prandtl number?
- Which kind of modeling for turbulent heat fluxes do we need?
- Which mesh quality do we have to ensure?

## Classification of heat transfer problems

| | |
|---|---|
| Steady or unsteady? | » RANS // LES/URANS |
| How many fluids? Do we have solids? | » single // CHT |
| Do we have phase change? | » singlephase // multiphase |
| Do we need radiation? | » Radiation models |
| Pressure or density driven flow? | » natural or forced convection |
| Turbulent or laminar? | » Turbulence Modeling |
| Fully developed or developing flow? | » Mesh quality |
| Fluid properties | » Mesh quality |

## Thermal boundary layer

- Very important lengthscale for numerical heat transfer simulation
- Often not considered. Parameter of last order.
- Be careful! Does not influence stability of simulation!
- However: Thermal boundary layer thickness is the most important parameter within the thermal simulation
- Thermal boundary of a flat plate



## Thermal boundary layer

- Thermal boundary develops when the surface temperature is different from the free stream temperature
- $T$ is a function of the wall normal distance $y$
- Defined as the y-location where

$$T - T_s = 0.99(T_s - T_\infty) \quad \frac{T - T_s}{T_s - T_\infty} = 0.99 \tag{6}$$

- The temperature gradient at the wall determines the local heat flux

$$Q/A = -k \frac{\partial T}{\partial x}\bigg|_{y=0} \tag{7}$$

## Thermal boundary layer

- Flat plate

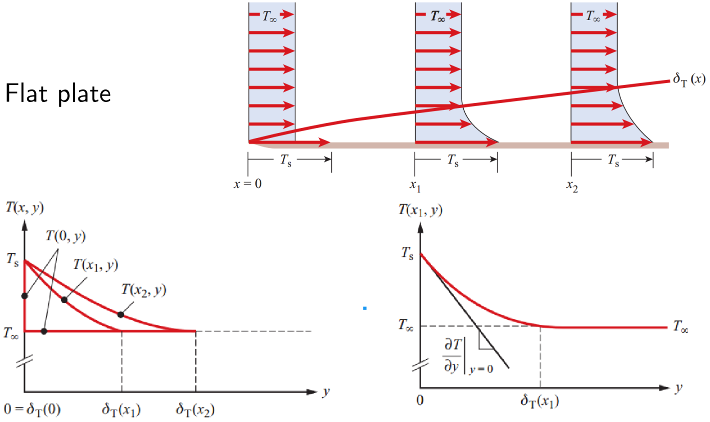



*Fig.: Thermal-Fluid Sciences, Turns*

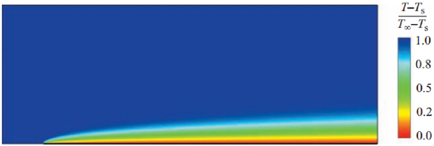
## Thermal boundary layer

- Calculation of heat tranfer coefficient

$$h_{conv} = Q/(A(T_f - T_s f)) \quad (8)$$

- Note: simple scaling of heat transfer coefficient

$$h_{conv,x} \approx \frac{k_f}{\delta_t(x)} \quad (9)$$




- Increasing $\delta_t$, decreasing temperature gradient $\rightarrow$ decreasing heat flux in flow direction

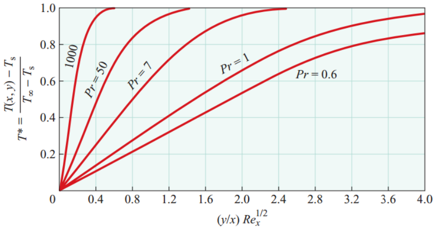
## Thermal boundary layer

- Note: for Pr=1 the temperature boundary layer profile is equal to the hydrodynamic solution!

$$\frac{u_x}{U_\infty} = (y/x)\mathrm{Re}_x^{0.5} \qquad T^* = (y/x)\mathrm{Re}_x^{0.5} \tag{10}$$

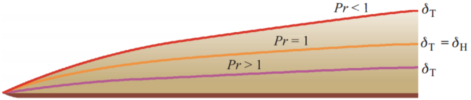
- Left picture gives us

$$\frac{\delta_t(x)}{x} = 5.0\mathrm{Re}_x^{-0.5}\mathrm{Pr}^{-1/3} \tag{11}$$

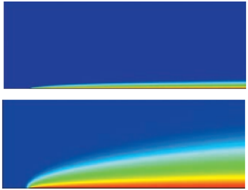


## Thermal boundary layer

- For Prandtl numbers greater than unity, the thermal boundary layer is thinner than the hydrodynamic boundary layer!




| Substance | Prandtl Number | |
|---|---|---|
| | At 300 K | At 400 K |
| Air | 0.707 | 0.690 |
| Hydrogen | 0.701 | 0.695 |
| Saturated steam | 0.857 | 1.033 |
| Mercury (liquid) | 0.0248 | 0.0163 |
| Saturated water | 5.83 | 1.47 |
| Engine oil | 6400 | 152 |



Pr=10

Pr=1.0

*Fig.: Thermal-Fluid Sciences, Turns*

## Practice Guide Lines

- Learned how to determine boundary layer thickness a priori
- Important to get an idea of the needed mesh sizes
- Best way:
  - Take a look at your geometry (plate, channel, pipe,....)
  - Use correlations for wall shear stress at a certain distance
  - Determine boundary layer thickness
  - Which fluid? –> thermal boundary layer thickness (remember: $slope \propto \mathrm{Pr}^{1/3}$
- Question:
  Which resolution is required to calculate trustable quantities like heat flux or wall shear stresses?

## Practice Guide Lines

- Learned how to determine boundary layer thickness a priori
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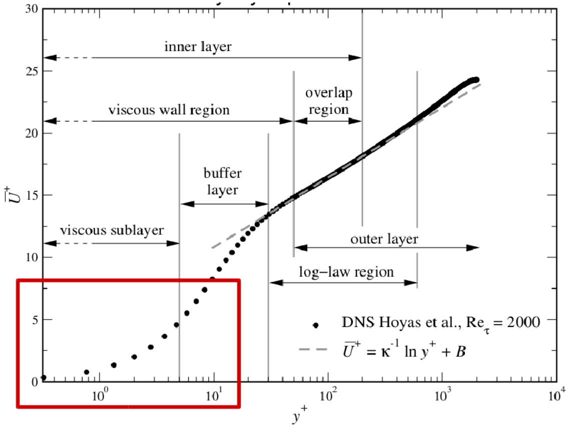
- Question:
  Which resolution is required to calculate trustable quantities like heat flux or wall shear stresses?
- Let's have a short look to the boundary layer theory

## Practice Guide Lines

- Uniform boundary layer profile



## Practice Guide Lines

- For air Pr $= 1.0$, $\delta_t = \delta_h$
- To calculate steady heat flux ($y^+ < 5$) is required without wall functions
- Be careful: only valid for steady calculations
- Time resolved heat transfer rate could be dramatically higher
  $\rightarrow$ Check your fluctuations near the wall
- Dramatic increase of near wall resolution when fluids with high Prandtl numbers (like water !!!) are present

## Practice Guide Lines

- Remember:

$$\frac{\delta_h}{\delta_t} = \mathrm{Pr}^{1/3} \tag{12}$$

- Thus the thermal boundary layer thickness is much smaller
- Increase wall resolution near the wall in dependence of Prandtl number
- If not possible: use wall functions!

Finish dry theoretical background!

## Overview of OpenFOAM solvers for heat transfer analysis

- **laplacianFoam:**
  Transient, incompressible, thermal diffusion according to Fourier's law
- **scalarTransportFoam:**
  Steady-state, incompressible, laminar, passive scalar e.g. temperature for a given velocity field
- **buoyantBoussinesqSimpleFoam:**
  Steady-state, thermal, natural convection, incompressible, Boussinesq's approximation
- **buoyantBoussinesqPimpleFoam:**
  Transient, thermal, natural convection, incompressible, Boussinesq's approximation

## Overview of OpenFOAM solvers for heat transfer analysis

- **buoyantSimpleFoam:**
  Steady-state, natural convection, compressible (sub-sonic), including radiation
- **buoyantPimpleFoam:**
  transient, natural convection, compressible(sub-sonic), including radiation
- **rhoSimpleFoam:**
  Steady-state, thermal, compressible(sub-sonic)
- **rhoSimplecFoam:**
  Steady-state, thermal, compressible(sub-sonic) -Pressure under relaxation =1
- **rhoPimpleFoam:**
  Transient, thermal, compressible(sub-sonic)

## Overview of OpenFOAM solvers for heat transfer analysis

- **chtMultiRegionFoam:**
  Transient, compressible, conjugate heat transfer between solid and fluid
- **chtMultiRegionSimpleFoam:**
  Steady-state, compressible, conjugate heat transfer between solid and fluid
- **thermoFoam:**
  Transient, evolves the thermophysical properties for a frozen velocity field

## Basic solver: laplacianFoam

- Simple heat conduction equation according to Fourier's law

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p} \frac{\partial^2 T}{\partial x^2} \tag{13}$$

- Take a look at the solver
  - `cd $FOAM_SOLVERS` or `sol`
  - `cd basic/laplacian`
  - `gedit laplacianFoam.C`

```
solve
(
fvm::ddt(T) - fvm::laplacian(DT, T)
);
```

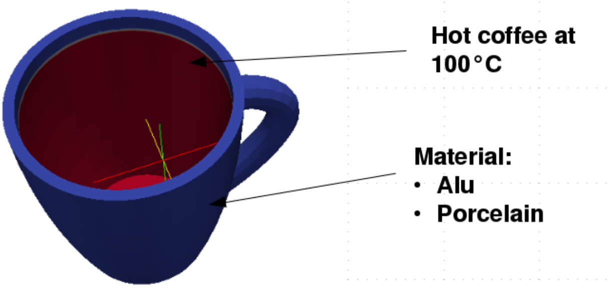
## Basic solver: laplacianFoam

- Define the heat diffusivity $DT$:
  - `gedit constant/transportProperties`

```
//DT = heat diffusivity
DT DT [ 0 2 -1 0 0 0 0 ] 1.6667e-05; //air
//DT DT [ 0 2 -1 0 0 0 0 ] 0.144e-06; //water
//DT DT [ 0 2 -1 0 0 0 0 ] 9.3e-05; //alu
```

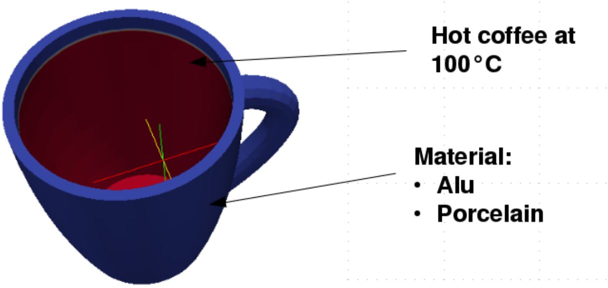
## Example coffee cup

- Using `laplacianFoam` to simulation usual problems
- Let's try to analyze the temperature distribution in our coffee cup



## Example coffee cup

- Using `laplacianFoam` to simulation usual problems
- Let's try to analyze the temperature distribution in our coffee cup
- Question: Can you touch the cup without any pain?



## Example coffee cup

- Setting the boundary conditions
- `gedit 0/T`

```
internalField uniform 273;
boundaryField
{
   sideWalls
  {
   type zeroGradient; //adiabatic
  }
   coffee
   {
   type fixedValue; // fixed Temperature b.c.
   value uniform 373;
   }
}
```

## Example coffee cup

- Setting the boundary conditions
- `gedit 0/T`

```
internalField uniform 273;
boundaryField
{
   sideWalls
  {
   type zeroGradient; //adiabatic
  }
   coffee
   {
   type fixedGradient; //fixed heat flux b.c.
   gradient 10000;
   value uniform 373;
   }
}
```

## Example coffee cup

- Define the heat diffusivity $DT$ for **alu**:
  - `gedit constant/transportProperties`

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//DT = heat diffusivity
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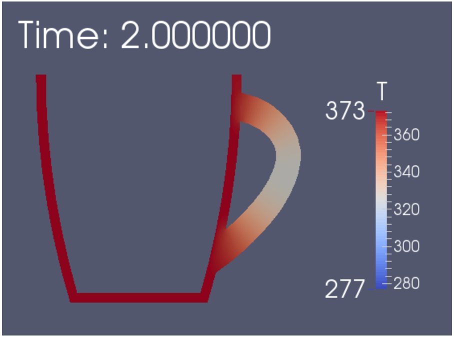
```

- `decomposePar`
- `foamJob -parallel laplacianFoam`
- `tail -f log`

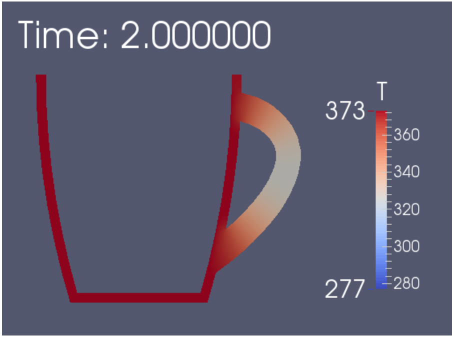
## Example coffee cup

- Take a look at the temperature after 2.0sec for our **alu** cup



## Example coffee cup

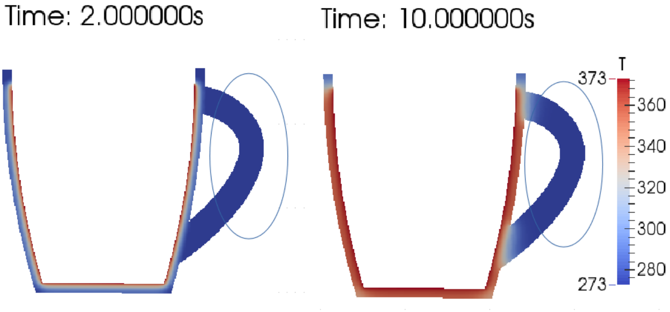
- Take a look at the temperature after 2.0sec for our **alu** cup




- The **alu** gives pretty hot fingers after 2.0sec ☺

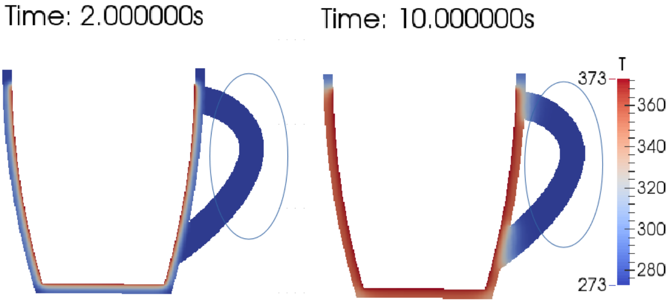
## Example coffee cup

- Comparison to a usual porcelain cup



## Example coffee cup

- Comparison to a usual porcelain cup




- The **porcelain** cup gives us cool fingers fingers after 2.0sec and 10.0sec (-:

## Outcome

- Laplacian solver gives a fairly good overview for simple heat conduction problems
- Always the first choice for simple heat conduction solutions
- First step: Think about which results you expect
- Important to avoid nonphysical solutions ... :-)
- Always take a look at the residuals
- Always remember that the mesh resolution influences the results in case of heat transfer dramatically!
- A Priori: Which boundary conditions should be applied?
- Be careful with the constant heat flux boundary condition

## Wich solvers can we use?

- **scalarTransportFoam** for laminar, unsteady/steady flows
- **buoyantBoussinesqSimpleFoam:**
  Steady-state, thermal, natural convection, incompressible, Boussinesq's approximation
- **buoyantBoussinesqPimpleFoam:**
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→ Set the gravitation to Zero for simple passive scalar flows

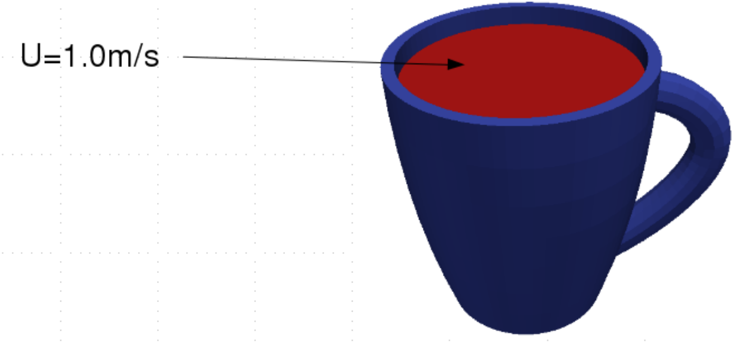
## Wich equation is solved?

```
   volScalarField alphaEff("alphaEff", turbulence->nu()/Pr
+ alphat);
```

```
   fvScalarMatrix TEqn
   (
      fvm::div(phi, T)
    - fvm::laplacian(alphaEff, T)
    ==
      radiation->ST(rhoCpRef, T)
      + fvOptions(T)
   );
```

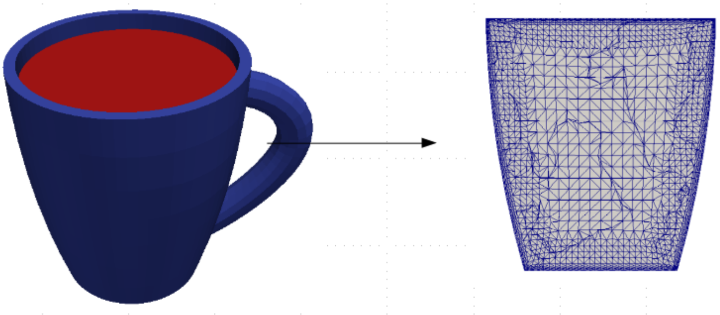
## Let's take a look at our cup!

- **Question**: How much is the coffee cooled down when you hold the cup in the cold wind of 0°C and a wind speed of 1.0m/s



## Let's take a look at our cup!

- Only the fluid is treated first



## Let's take a look at our cup!

- Do we need turbulence?

$$\mathrm{Re} = \frac{U \cdot L}{\nu} = \frac{1m/s \cdot 0.05m}{0.3 \cdot 10^{-06} m/s^2} = 16666 \quad (14)$$

## Let's take a look at our cup!

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$$\mathrm{Re} = \frac{U \cdot L}{\nu} = \frac{1 m/s \cdot 0.05 m}{0.3 \cdot 10^{-06} m/s^2} = 16666 \tag{14}$$

- Yes weed need turbulence.
- Turbulence model → kOmegaSST (wallbounded)
- `gedit constant/RASProperties`

```
 simulationType RAS;
RAS
{
 RASModel kOmegaSST;
 turbulence on;
 printCoeffs on;
}
```

## Let's take a look at our cup!

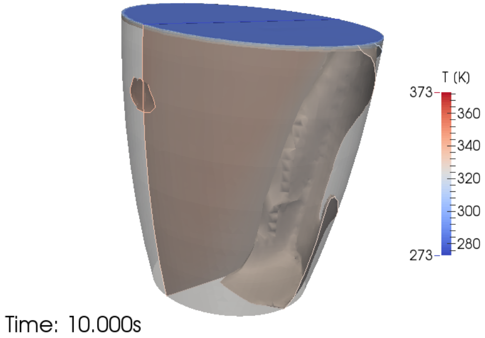
- We need Prandtl numbers for coffee
- Assuming hot water at 373K
  - $\mathrm{Pr} = 1.75$
  - Turbulent Prandtl number Prt ?
  - Normally a dynamic calculation!
  - Here: fixed at $\mathrm{Pr}_t = 0.9$
- Please remember: turbulent Prandtl number is not a constant
- Varies through the boundary layer!
- Set the value in `constant/transportProperties`

## Get the simulation started!

- `foamJob -parallel buoyantBoussinesqPimpleFoam`

## Get the simulation started!

- `foamJob -parallel buoyantBoussinesqPimpleFoam`
- Result after 10sec



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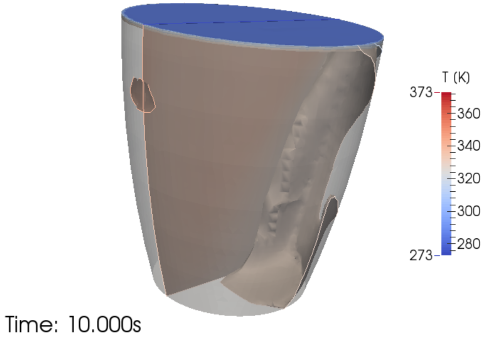


- Mean temperature using paraview volume integration 62.4°C

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- Mistakes may occur. Any ideas?

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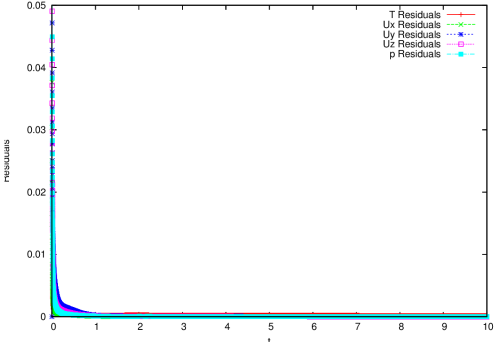
- Look at the residuals



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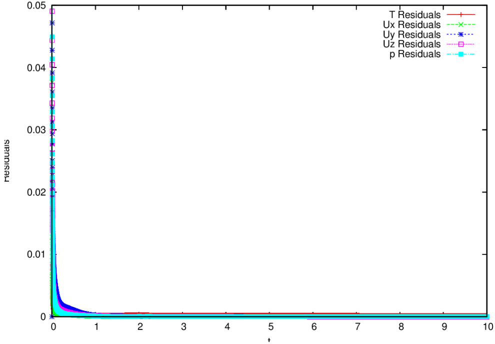


- Ok, high residuals within the first time step! Smaller timesteps at the beginning of the simulation!

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- Look at the mesh resolution for heat transfer analysis

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- Mistakes may occur. Any ideas?
- Look at the mesh resolution for heat transfer analysis
- Remember the theory of a flate plate

$$\mathrm{Re}_l = \frac{U \cdot L}{\nu} = \frac{1m/s \cdot 0.025m}{0.3 \cdot 10^{-06} m/s^2} = 16666 \quad (15)$$

$$\frac{\delta_h}{L} = 5.0\mathrm{Re}_l = 0.0173m \quad (16)$$

$$\delta_h = 0.4 \cdot 10^{-03} m \quad (17)$$

## Analyze your results

- Mistakes may occur. Any ideas?
- Look at the mesh resolution for heat transfer analysis
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$$\frac{\delta_h}{L} = 5.0 \mathrm{Re}_l = 0.0173 m \tag{16}$$

$$\delta_h = 0.4 \cdot 10^{-03} m \tag{17}$$

- Let's check our mesh!

## Analyze your results

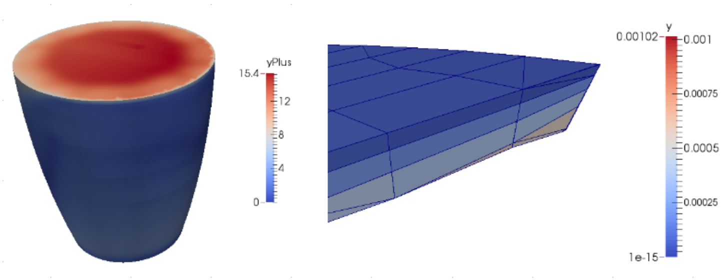
- ```
  yPlus -latestTime
  Patch 0 named cup_fluid_surface, wall-function
  nutLowReWallFunction, y+ :  min:  8.21955 max:
  15.8498 average:  13.0949
  Patch 1 named cup_fluid_wall, wall-function
  nutLowReWallFunction, y+ :  min:  0.287126 max:
  7.86749 average:  3.2015
  ```
- Not good, we need to generate a finer mesh!
- Also remember the correlation of thermal and hydraulic boundary layer

$$\frac{\delta_h}{\delta_t} = \mathrm{Pr}^{1/3} \tag{18}$$

- We need to be finer at the coffee surface!
- Fields of y and yPlus are written to the time folder
  ```

## Analyze your results

- Mesh resolution




- Mesh is too coarse near the wall!

## Analyze your results

- Now you have the choice:
  1. Generate a finer mesh.
  2. Application of wall functions.
- OpenFOAM gives us a wallfunction called `alphatJayatillekeWallFunction`
- Application of the wallfunction to obtain the turbulent thermal conductivity at the wall to ensure realistic heat flux

$$\mathrm{alpha}_t = \frac{\nu}{\mathrm{Pr}} + \frac{\nu_t}{\mathrm{Pr}_t} \tag{19}$$

## Analyze your results

- OpenFOAM gives us a wallfunction called `alphatJayatillekeWallFunction`
- ```
  cup_fluid_surface
   {
      type alphatJayatillekeWallFunction;
      Prt 0.9;
      value uniform 0;
   }
   cup_fluid_wall
   {
      type alphatJayatillekeWallFunction;
      Prt 0.9;
      value uniform 0;
   }
  ```
  ```

## Get back starting the simulation

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## Get back starting the simulation

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- Result after 10sec
- Mean temperature using paraview volume integration is now 58.4°C compared to previous 62.4°C

## Get back starting the simulation

- `foamJob -parallel buoyantBoussinesqPimpleFoam`
- Result after 10sec
- Mean temperature using paraview volume integration is now 58.4°C compared to previous 62.4°C
- Higher temperature gradients need to be captured using a finer mesh or by application of wallfunctions.

## Remember

- a) Residuals
- b) Mesh resolution
- c) turbulent boundary conditions
- d) upwind schemes for velocity and temperature are too diffusiv! (see `system/fvSchemes`)
- application of finer and high quality meshes allow us to use second order schemes like `Gauss linear` or `linearUpwind` or blended schemes like `Gauss linearLimited`

## Including buoyant forces

- Calculate temperature profiles in case of natural convection problems using Boussinesq approximation for density changing in stratified flows

$$\rho_{eff} = 1 - \beta(T - T_{ref}) \qquad (20)$$

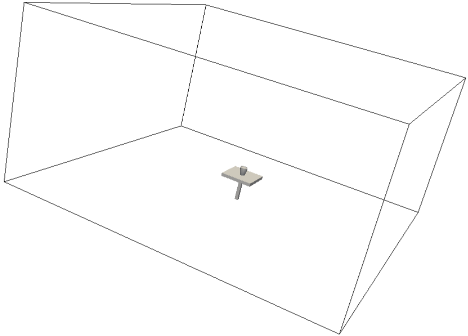
- where

| | |
|---|---|
| $\rho_{eff}$ | effective driving density |
| $\beta$ | thermal expanison coefficient |
| $T$ | temperature |
| $T_{ref}$ | reference temperature |

- Note:
  - Boussinesq approximation is only valid for $\beta(T - T_{ref} \ll 1.0)$
  - According to *Peric* the failure is below 1% for temperature differences of max. 2K for water and 15K for air

## Including buoyant forces

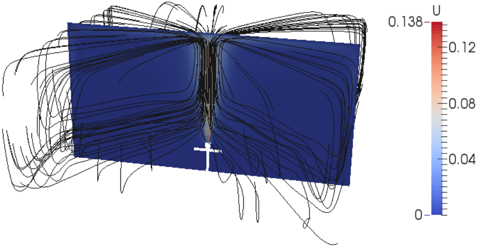
- Let's place our cup in a room on a small table



- `foamJob -parallel buoyantBoussinesqSimpleFoam`

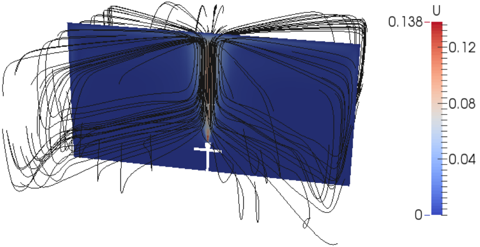
## Including buoyant forces

- Look at the results:



## Including buoyant forces

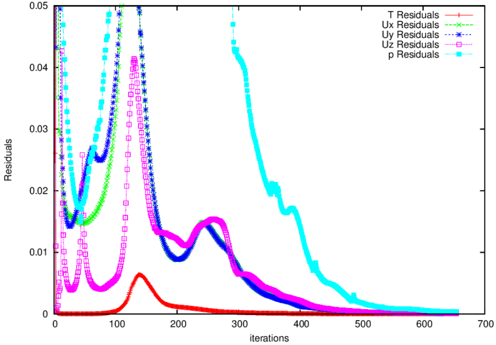
- Look at the results:




- Streamlines seems to be physically reasonable

## Including buoyant forces

- But, take a look at the residuals!




- Seems to be ok, but remember that the convergence of steady simulations using Boussinesq approximation is hard to get.

## Including buoyant forces

- Remember, that we have a temperature difference about 100K, Boussinesq approximation is not guilty!
  max 15K for air
- I have used upwind to get convergence.
  The applied interpolation schemes are to diffusive –> temperature disappears in the solution after a short range better use `bounded Gauss linearUpwind grad(U)`
- Better divergence schemes shows no convergence for this case :-)
- Use `buoyantBoussinesqPimpleFoam` if possible!

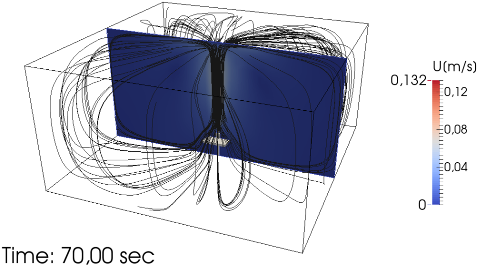
## Including buoyant forces

- Run `foamJob buoyantBoussinesqPimpleFoam`
- Trying to get convergence for each timestep → good for initial heat transfer calculations
- `gedit log`

```
DILUPBiCG: Solving for T, Initial residual =
2.04079e-06, Final residual = 2.53797e-08, No
Iterations 1
DICPCG: Solving for p_rgh, Initial residual =
0.0287143, Final residual = 0.000274784, No Iterations
33
DICPCG: Solving for p_rgh, Initial residual =
0.00027785, Final residual = 2.6717e-06, No Iterations
53
```

## Including buoyant forces

- Here is the result after 70sec of realtime



## Compressible buoyant forces

- Since our coffee is too hot for the Boussinesq approximation we have to include the variation of material properties through pressure and temperature Relevant solvers are
- `buoyantSimpleFoam`:
  Steady-state, natural convection, compressible (sub-sonic), including radiation
- `buoyantPimpleFoam`:
  transient, natural convection, compressible(sub-sonic), including radiation

## Compressible buoyant forces

- Changing of material properties requires underlaying thermophysics of the fluids
- Generally the thermophysics within OpenFOAM are a little bit of a mysterium since it is not well documented
- Let's bring light into the darkness
- Thermophysical properties for each case are defined in `constant/thermophysicalProperties`
- All models are located under `$FOAM_SRC/thermophysicalModels`
  - Fluid and solid properties (water, air)
  - Mixture and pre-definitions for combustion (really complicated ....)

## Thermophysical models

- Thermomodels are the basis for determination of all material quantities
- Most of the models are implemented for combustion simulations since the temperature and pressure variations are enormously
- Models needed for heavy reactions are based on compressibility
- For heat transfer analysis only **density** based models are relevant
- Otherwise phase changing is present which requires VOF methods including a fast interface capturing (see Level Set methods, big pain for unstructured meshes ...)

## Thermophysical models

- `gedit constant/thermophysicalProperties`

```
 thermoType
{
    type heRhoThermo;
    mixture pureMixture;
    transport const;
    thermo hConst;
    equationOfState perfectGas;
    specie specie;
    energy sensibleEnthalpy;
}
```

## Thermophysical models

- Types of thermo class

| | |
|---|---|
| `hePsiThermo` | General thermophysical model calculation based on compressibility $\psi = 1/(RT)$<br>Only gas |
| `hRhoThermo` | General thermophysical model calculation based on density $\rho$<br>Gas, liquid, solids |
| `hSolidThermo` | Only solids |

## Thermophysical models

- Let's look for the air
- gedit constant/thermophysicalProperties

```
thermoType
{
    type heRhoThermo;
    mixture pureMixture;
    transport polynomial;
    thermo hPolynomial;
    equationOfState icoPolynomial;
    specie specie;
    energy sensibleEnthalpy;
}
```

## Thermophysical models

- Let's look for the air
- `gedit constant/thermophysicalProperties`

```
mixture
{
// coefficients for air
   specie
  {
   nMoles 1;
   molWeight 28.85;
   }
   equationOfState
   {
   rhoCoeffs<8> ( 4.0097 -0.016954 3.3057e-05
-3.0042e-08 1.0286e-11 0 0 0 );
   }
```

## Thermophysical models

- Let's look for the air
- `gedit constant/thermophysicalProperties`

```
thermodynamics
   {
   Hf 0;
   Sf 0;
   CpCoeffs<8> ( 948.76 0.39171 -0.00095999 1.393e-06
-6.2029e-10 0 0 0 );
   }
  transport
   {
  muCoeffs<8> ( 1.5061e-06 6.16e-08 -1.819e-11 0 0 0 0
0 );
   kappaCoeffs<8> ( 0.0025219 8.506e-05 -1.312e-08 0 0
0 0 0 );
   }
```

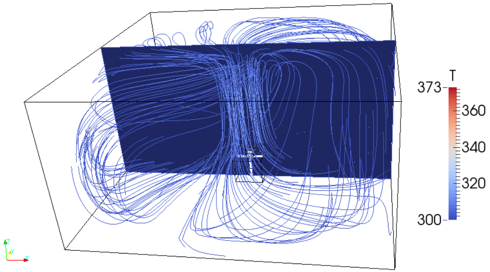
## Thermophysical models

- Just make a small mistake to see which combination is possbile!

```
thermoType
{
    type heRhoThermo;
    mixture pureMixture;
    transport polynomial;
    thermo hPolynomial;
    equationOfState icoPolynomial;
    specie bananas;
    energy sensibleEnthalpy;
}
```

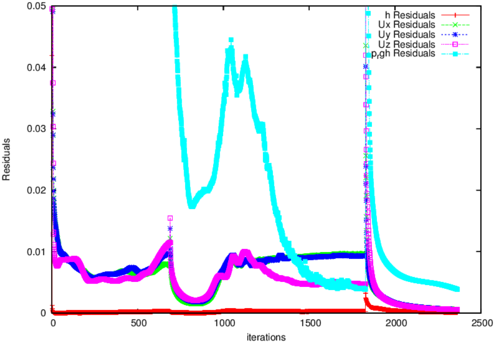
## Run the compressible case

- Now we are able to run the simulation with changing material parameters
- `foamJob -parallel buoyantSimpleFoam`



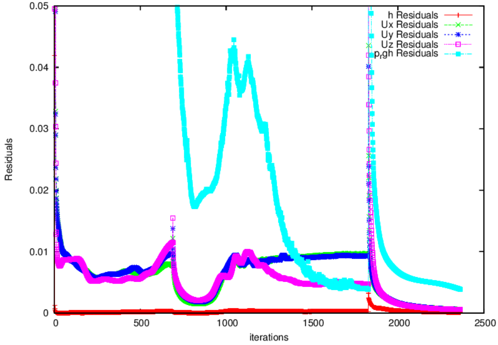
## Run the compressible case

- Keep care of the residuals



## Run the compressible case

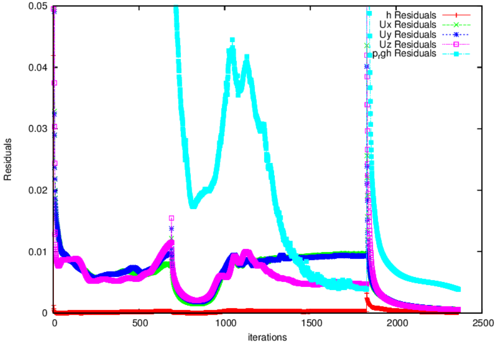
- Keep care of the residuals




- Large residuals → hard to get convergence for steady simulations.

## Run the compressible case

- Keep care of the residuals




- Large residuals → hard to get convergence for steady simulations.
- Better use unsteady solver `buoyantPimpleFoam`

## Case Setup

- Let's get to interesting stuff
- Including solids and more fluids in the analysis
- Names of the regions are defined in the file `constant/regionProperties`
- For our case:

```
regions
  (
   fluid (air coffee)
   solid (cup)
  );
```

## Case Setup

- Eeach region properties are defined separately in the folders `0,constant,system`
- All other parameters for each region are defined in the region folders (e.g. `ls system/air`)
- A useful tool to setup the simulations: `changeDictionaryDict`
- Initialize the start fields for e.g. the region air `changeDictionary -region air`
- However be careful, empty fields are required

## Case setup

- `gedit 0/air/T`

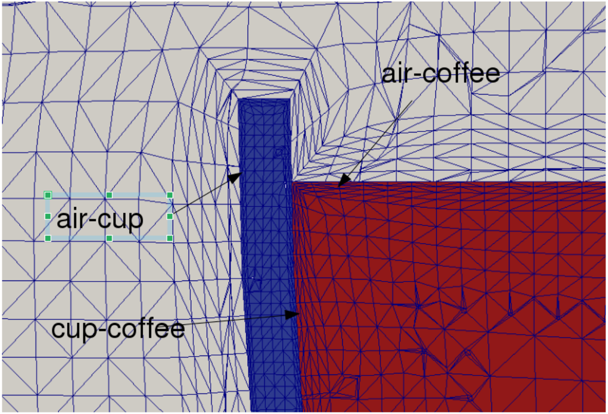
```
air_cup
   {
   type
compressible::turbulentTemperatureCoupledBaffleMixed;
   Tnbr T;
   kappa fluidThermo;
   kappaName none;
   value uniform 300;
   }
```

- Additional multiple layers with different thermal resistances can be specified at the interface:

```
thicknessLayers (1e-3);
kappaLayers (5e-4);
```

## Case setup

- Lets's look at our interfaces:



## Case setup

- `gedit constant/air/polyMesh/boundary`

```
air_cup
  {
   type mappedWall;
   sampleMode nearestPatchFace;
   sampleRegion cup;
   samplePatch cup_air;
   nFaces 3307;
   startFace 616900;
  }
```

## Case setup

- Coupling is based on nearest neighbor search!
- So please be careful to couple meshes with totally different mesh resolutions at the wall
- Otherwise the interpolation will give bad results
- Also remember, that the heat fluxes are not strictly conservative
- Too strong differences in the mesh resolution will induce heat sinks or heat source at the coupled patches

## Run the CHT Case

- After the long road of setting up the case
- `decomposePar -allRegions`
  `foamJob -parallel chtMultiRegionFoam`
- After finish the simulation
- `paraFoam -touchAll`
- `paraview`

## Analyze the results

- Let's have look what our alu cup says

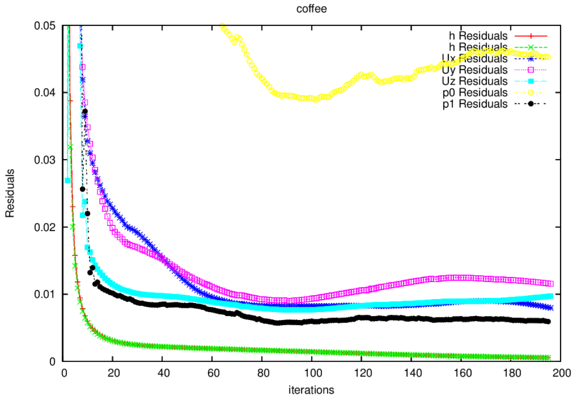
## Analyze the results

- Let's have look what our alu cup says


- Your hand will be quite hot after 1 sec :-)

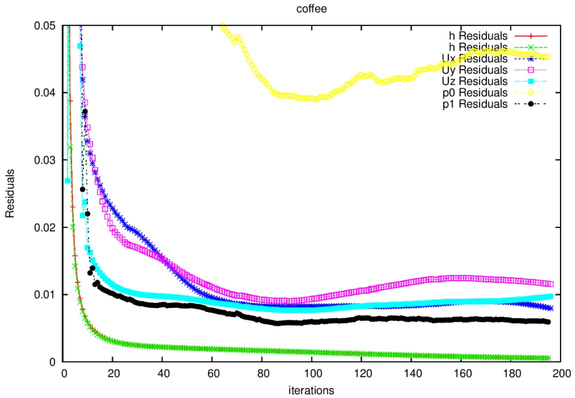
## Analyze the results

- Check the residuals!



## Analyze the results

- Check the residuals!




- Not good for the coffee fluid.

## Analyze the results

- Use `potentialFoam` to get initial flow fields
- Use strong under relaxation for *p_rgh* and *h*
- Especially for heat transfer the temperature range is enlarged for in areas of bad cells or high velocity gradients
- Easy way to limit the temperature range is to use the very comfortable `fvOptions` method
- `fvOptions` can be added individually to the solver (e.g. porosity, ..)
- No need to recompile and adopt solver properties
- Located `$FOAM_SRC/fvOptions`

## Analyze the results

- gedit system/air/fvOptions

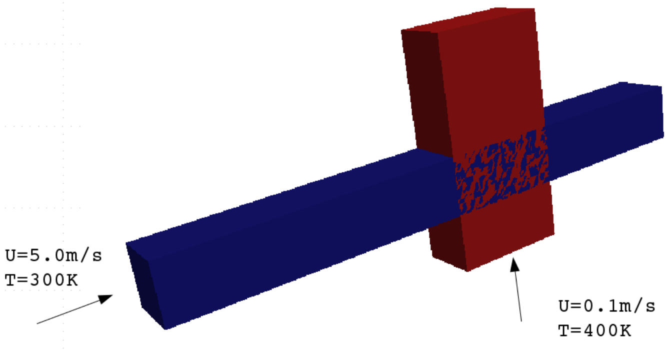
```
temperature_corrections
  {
   type limitTemperature;
   active yes;
   selectionMode all;
   limitTemperatureCoeffs
      {
      selectionMode all;
      Tmin 300;
      Tmax 373;
      }
  }
```

## Using `fvOptions`

- OpenFOAM gives us the following possibilities
  - `constantHeatTransfer`
    Constant heat transfer coefficient, need Area to Volume ratio (AoV)
  - `variableHeatTransfer`
    Calculates heat transfer coefficient using Nusselt number correlation
    $Nu = a * pow(Re, b) * pow(Pr, c)$
  - `tabulatedHeatTransfer`
    Calculates heat transfer coefficient using a predefined 2D table for heat transfer coefficient and velocity
- Interpolation of enthalpy h between each fluid region

## Using `fvOptions`

- Let's solve the heat exchange between to cross streams of water and air



## Using fvOptions

- The coupling is defined in system/air/fvOptions
- gedit system/air/fvOptions

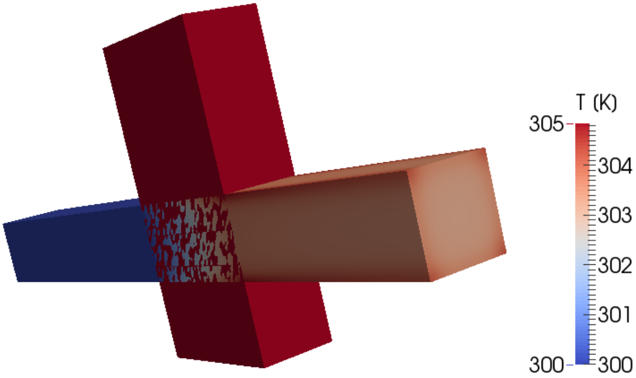
```
air_water
   {
  type constantHeatTransfer;
  active on;
  selectionMode mapRegion;
  interpolationMethod cellVolumeWeight;
  nbrRegionName water;
  master true
...
```

## Using `fvOptions`

- We have to provide the Area of Volume ratio (AoV)
- `gedit 0/air/AoV`
- And the constant heat transfer coefficient
- `gedit 0/air/htcConst`
- `foamJob chtMultiRegionSimpleFoam`

## Using `fvOptions`

- Look at the results



## Using `fvOptions`

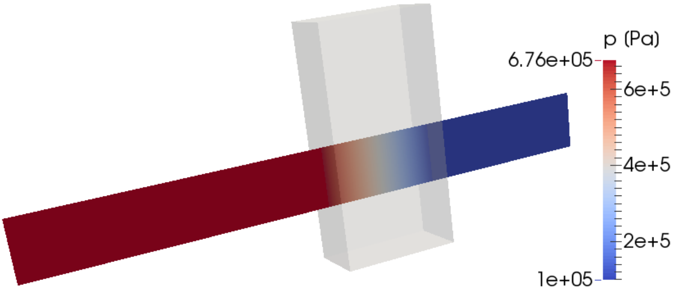
- However, the regions do not only interact through heat transfer
- Flow resistance due to e.g. heat exchanger pipes is present inducing a pressure drop
- Without modeling each pipe the flow resistance is included using porosity models
- OpenFOAM uses Darcy-Forchheimer law to calculate pressure drop

$$S_i = -[\mu d_i + 0.5\rho |u_i| f_i] u_i \tag{21}$$

- Please note, that the porosity can be defined for a cellZone (`explicitPorositySource`) or a region (`interRegionExplicitPorositySource`)

## Using fvOptions

- If we add the porosity we get pretty physical results inside complex heat exchangers



- **Let's have short break!**

## Basic background

- Radiation is very important and is often not considered
- Interaction of different devices in respect of thermal radiation is basis of thermal problems
- Throw radiation heat transfer beside will often lead to wrong physical results a
- Radiation heat transfer takes place in form of electromagnetic waves
- Wave length for heat transfer: $0.8 - 400 \mu m$ (ultrared)
- At higher temperatures, the amount of visible radiation is larger and can be seen e.g. lightning bulb

## Basic background

- With increasing temperatures the intensity of heat radiation increases e.g. the human body radiates continuously about 1000W in a vacuum
- (note: no media is required for thermal radiation)
- From surrounding walls the human adsorbs thermal energy of about 900W
- So the typical loss of a non-working human is about 100W
- Electromagnetic waves can be adsorbed, reflected or transmitted according to the surface properties

$$\epsilon + \tau + \rho = 1 \tag{22}$$

- Coefficients depend also on wave length

## Basic background

- For simplification a black body is introduced
  - All waves are adsorbed
  - Waves are emitted with maximum of intensity
- Emission coefficient for a black body is $\epsilon = 1$
- Law of Kirchhoff $\epsilon = \alpha$

## Basic background

- The emission for a black body is independent of the wave length and solid angle
- Stephan-Boltzmann-law for hemispheric thermal radiation

$$Q/A = \epsilon\sigma T^4 \qquad \sigma = 5.6696 \cdot 10^{-8} W/m^2 K^4 \tag{23}$$

- Remember: include radiative heat transfer when the radiant heat flux, is large compared to the heat transfer rate due to convection or conduction

$$q_{rad} = \sigma(T_{max}^4 - T_{min}^4) \tag{24}$$

## Basic background

- OpenFOAM gives us three radiation models to calculate the heat fluxes
  - P1 model
  - fvDOM (finite volume discrete ordinates model)
  - viewFactor model

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- OpenFOAM gives us three radiation models to calculate the heat fluxes
  - P1 model
  - fvDOM (finite volume discrete ordinates model)
  - viewFactor model
- We don't have time to review the models!
- But let us take a closer look

## Decision of radiation model

- Indicator is the optical length $a * L$ where $L$ is typical length scale and $a$ absorption coefficient
- If $a * L >> 1$ then use P1 model
- Otherwise if $a * L < 1$ use fvDOM
- Since fvDOM also captures the large optical length scales it is the most accurate model
- P1 model tends to overpredict the heat flux
- fvDOM consumes a lot of CPU power since it solves the transport equation for each direction
- fvDOM can handle non gray surfaces (dependence of the solid angle is included)
- viewFactor is used if non participating mediums are present (space craft, solar radiation)

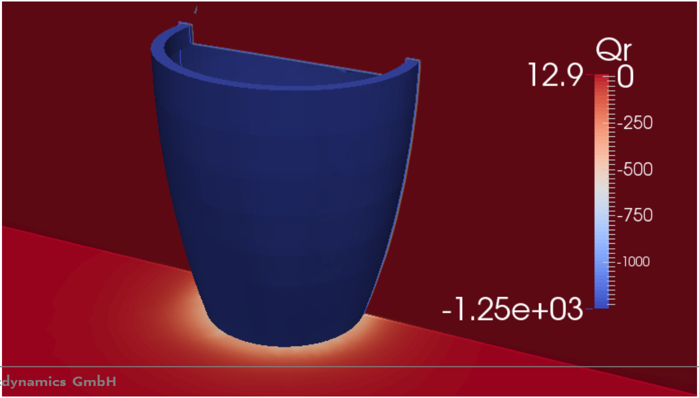
## Get the case started

- gedit constant/radiationProperties

```
radiation on;
radiationModel P1;
// Number of flow iterations per radiation iteration
solverFreq 1;
absorptionEmissionModel constantAbsorptionEmission;
constantAbsorptionEmissionCoeffs
{
absorptivity absorptivity [ m^-1 ] 0.5;
emissivity emissivity [ m^-1 ] 0.5;
E E [ kgm^-1s^-3 ] 0;
}
scatterModel none;
sootModel none;
```

## Get the case started

- We have to define the incident radiation field $G$ for the P1 model
- And the field for radiation intensity $I$ in case of the fvDOM model
- Let's look at the radiative heat flux $Qr$ for the P1 model



## Get the case started

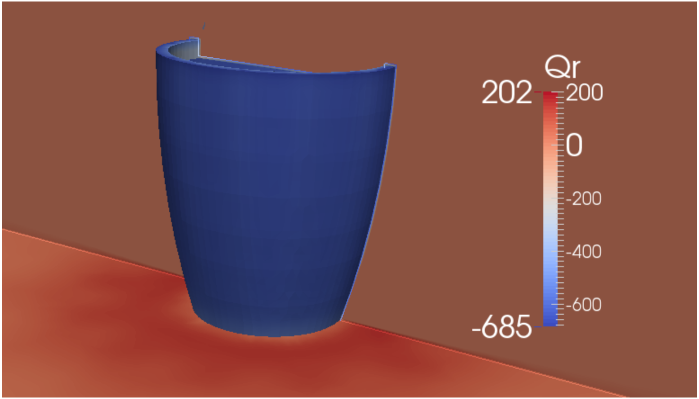
- Properties for the fvDOM

```
nPhi 3; // azimuthal angles in PI/2 on X-Y.(from Y to X)
nTheta 4; // polar angles in PI (from Z to X-Y plane)
convergence 1e-3; // convergence criteria for radiation
iteration
maxIter 10; // maximum number of iterations
cacheDiv false; //only for upwind schemes
```

- Hence for 4 Octants this gives us 48 equations for the intensity
- To get a numerical stable solution, a maximum iteration of 10 is defined
- Very time consuming: 480 Iterations per timeStep
- Thus only every 10 iterations the number of equations are solved (`solverFreq 10`)

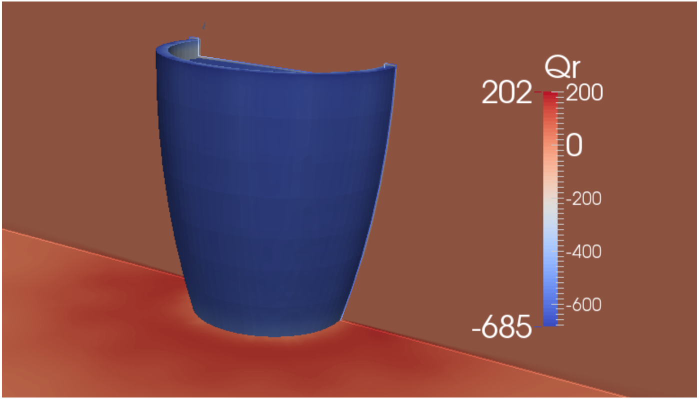
## Get the case started

- Radiative heat flux for the fvDOM



## Get the case started

- Radiative heat flux for the fvDOM



## Outcome

- FvDOM model much more physical
- P1 model overpredict heat flux at cup and table surface
- Remember the optical length a*L!
- Radiative heat transfer from the hot cup to cold table has a fairly small
- length scale –> small optical length –> fvDOM
- FvDOM requires large CPU resources
- Use viewFactor model for solar radiation

**Thank you very much!**

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