Coupling of VOF with LPT in OpenFOAM

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1 Multiphase flow methods
- VOF
- VOF in OpenFOAM
- LPT
- LPT in OpenFOAM

2 Tutorial
- Add a LPT solver to interFoam
- Add a particle injector
- Add two-way coupling
- Add four-way coupling
  - A deterministic model for collision
  - Implementation in OpenFoam
  - The outcome of collision
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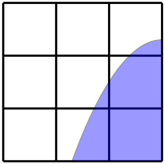
  - Grid refinement
  - Set the volume fraction to 1 in the bottom region
  - Implement a algorithm which switch from LPT to VOF when the particle is close enough to a VOF interface

VOF (Volume Of Fluid)



- Bubbles/droplets larger than the grid size
- Irregular structures: need to describe the interface

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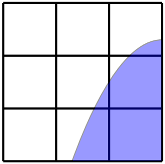
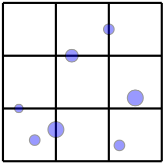


- Bubbles/droplets larger than the grid size
- Irregular structures: need to describe the interface

LPT (Lagrangian Particle Tracking)



- Bubbles/droplets smaller than the grid size
- Shape can be considered spherical

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Liquid volume fraction $\alpha \in [0, 1]$.

$$\rho = \alpha \rho_l + (1 - \alpha)\rho_g,$$

$$\mu = \alpha \mu_l + (1 - \alpha)\mu_g,$$

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Transport equation for the liquid volume fraction

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Mass and momentum equations for the mixture

$$\nabla \cdot \mathbf{U} = 0,$$

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = -\nabla p + \mu \nabla^2 \mathbf{U} + \rho \mathbf{g} - \mathbf{S_{st}} + \mathbf{S_P}.$$

$$\mathbf{S_{st}} = \sigma_{st}\kappa\delta\mathbf{n}\ ,\ \mathbf{n} = \frac{\nabla\alpha}{|\nabla\alpha|}\ ,\ \kappa = \nabla\mathbf{n}.$$

ls $WM_PROJECT_DIR/applications/solvers/multiphase/interFoam

```
alphaEqn.H
alphaEqnSubCycle.H
correctPhi.H
createFields.H
interFoam.C
Make
pEqn.H
UEqn.H
```

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vi createFields.H

```
Info<< "Reading field alpha1" << endl;
    volScalarField alpha1
    (
        IOobject
        (
            "alpha1",
            runTime.timeName(),
            mesh,
            IOobject::MUST_READ,
            IOobject::AUTO_WRITE
        ),
        mesh
    );
```

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$$\rho = \alpha\rho_g + (1-\alpha)\rho_l$$

vi createFields.H

```
Info<< "Reading transportProperties" << endl;
twoPhaseMixture twoPhaseProperties(U, phi, "alpha1");
const dimensionedScalar& rho1 = twoPhaseProperties.rho1();
const dimensionedScalar& rho2 = twoPhaseProperties.rho2();
 volScalarField rho
    (
        IOobject
        (
            "rho",
            runTime.timeName(),
            mesh,
            IOobject::READ_IF_PRESENT
        ),
        alpha1*rho1 + (scalar(1) - alpha1)*rho2,
        alpha1.boundaryField().types()
    );
```

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$$\mu = \alpha\mu_g + (1-\alpha)\mu_l$$

vi $WM_PROJECT_DIR/src/transportModels/incompressible/incompressibleTwoPhaseMixture/twoPhaseMixture.C

```
Foam::tmp<Foam::volScalarField> Foam::twoPhaseMixture::mu() const
{
   const volScalarField limitedAlpha1
   (
       min(max(alpha1_, scalar(0)), scalar(1))
   );
   return tmp<volScalarField>
    (
       new volScalarField
        (
           "mu",
           limitedAlpha1*rho1_*nuModel1_->nu()
          + (scalar(1) - limitedAlpha1)*rho2_*nuModel2_->nu()
         )
     );
 }
```

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vi alphaEqn.H

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vi UEqn.H

```
solve
   (
       UEqn
    ==
       fvc::reconstruct
       (
           (
               fvc::interpolate(interface.sigmaK())*fvc::snGrad(alpha1)
             - ghf*fvc::snGrad(rho)
             - fvc::snGrad(pd)
           ) * mesh.magSf()
       )
   );
```

Now, what is interface.sigmaK() ?

- Go to the online documentation: http://foam.sourceforge.net/docs/cpp/
- Search for sigmaK and select the hint Foam::interfaceProperties::sigmaK()
- Select the link "line 140 of the file interfaceProperties.H."

```
00140        tmp<volScalarField> sigmaK() const
00141        {
00142            return sigma_*K_;
00143        }
00144
00145        void correct()
00146        {
00147            calculateK();
00148        }
```

- Go to the description of the function calculateK() in **interfaceProperties.C**

```
00123    // Face unit interface normal
00124    surfaceVectorField nHatfv(gradAlphaf/(mag(gradAlphaf) + deltaN_));
00126
00127    // Face unit interface normal flux
00128    nHatf_ = nHatfv & Sf;
00129
00130    // Simple expression for curvature
00131    K_ = -fvc::div(nHatf_);
```

- At line 164, you can also see that sigma is read in the dictionary "tranportProperties"

```
00164    sigma_(dict.lookup("sigma")),
```

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Particle P: position $\mathbf{x_P}$, diameter D_P, velocity $\mathbf{U_P}$ and density ρ_P.

$$\frac{d\mathbf{x_P}}{dt} = \mathbf{U_P},$$

$$m_P \frac{d\mathbf{U_P}}{dt} = \sum \mathbf{F}.$$

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Two-way coupling:

$$\mathbf{S_P} = \frac{1}{V_{cell}\Delta t} \sum_P m_P((\mathbf{U_p})_{t_{out}} - (\mathbf{U_p})_{t_{in}})$$

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Four-way coupling: particle-particle collisions.

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ls $WM_PROJECT_DIR/src/lagrangian/solidParticle/

```
lnInclude
Make
solidParticle.C
solidParticle.H
solidParticleI.H
solidParticleIO.C
solidParticleCloud.C
solidParticleCloud.H
solidParticleCloudI.H
```

Particle P: position $\mathbf{x_P}$, diameter D_P, velocity $\mathbf{U_P}$ and density ρ_P.

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Particle P: position $\mathbf{x_P}$, diameter D_P, velocity $\mathbf{U_P}$ and density ρ_P.

vi solidParticle.H

```
inline solidParticle
(
    const Cloud<solidParticle>& c,
    const vector& position,
    const label celli,
    const scalar m,
    const vector& U
);
```

Particle P: position $\mathbf{x_P}$, diameter D_P, velocity $\mathbf{U_P}$ and density ρ_P.

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    const Cloud<solidParticle>& c,
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);
```

vi solidParticleI.H

```
inline Foam::solidParticle::solidParticle
(
    const Cloud<solidParticle>& c,
    const vector& position,
    const label celli,
    const scalar d,
    const vector& U
)
```

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(
    const Cloud<solidParticle>& c,
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    const label celli,
    const scalar d,
    const vector& U
)
```

vi solidParticleCloud.C

```
rhop_(dimensionedScalar(particleProperties_.lookup("rhop")).value()),
```

Particle P: position $\mathbf{x_P}$, diameter D_P, velocity $\mathbf{U_P}$ and density ρ_P.

$$\frac{d\mathbf{x_P}}{dt} = \mathbf{U_P},$$

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Four-way coupling: particle-particle collisions.

$$\frac{d\mathbf{x_P}}{dt} = \mathbf{U_P},$$

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vi solidParticle.C

```
dt *= trackToFace(position() + dt*U_, td);
tEnd -= dt;
stepFraction() = 1.0 - tEnd/deltaT;
...
scalar Dc = (24.0*nuc/d_)*ReFunc*(3.0/4.0)*(rhoc/(d_*rhop));
U_ = (U_ + dt*(Dc*Uc + (1.0 - rhoc/rhop)*td.g()))/(1.0 + dt*Dc);
```

Now, what is trackToFace ?

- Go to the online documentation:
  http://foam.sourceforge.net/docs/cpp/
- Search for trackToFace and select the hint Foam::particle

```
Foam::scalar trackToFace(const vector & endPosition,
                         TrackData & td
                         )
```

```
Track particle to a given position and returns 1.0 if the trajectory is
completed without hitting a face otherwise stops at the face and returns
the fraction of the trajectory completed. on entry 'stepFraction()'
should be set to the fraction of the time-step at which the tracking starts.
Definition at line 202 of file particleTemplates.C.
```

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NOT IMPLEMENTED

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1. Add a LPT solver to track small particles in the multiphase solver interFoam
2. Add a particle injector
3. Add two-way coupling (source term S_P in the momentum equation of interFoam)
4. Add four-way coupling (add a model for particle-particle collision)
5. Convert particle to VOF when it comes close to a VOF interface

```
cd $WM_PROJECT_USER_DIR/applications
mkdir myLPTVOF
cd myLPTVOF

cp -r $WM_PROJECT_DIR/applications/solvers/multiphase/interFoam/* .

cp  $WM_PROJECT_DIR/src/lagrangian/solidParticle/* .
```

vi Make/files

```
interFoam.C
solidParticle.C
solidParticleIO.C
solidParticleCloud.C
EXE = $(FOAM_USER_APPBIN)/myLPTVOF
```

vi Make/options

```
-I$(LIB_SRC)/lagrangian/basic/lnInclude\
-I$(LIB_SRC)/finiteVolume/lnInclude

-lfiniteVolume \
-llagrangian \
-lsolidParticle \
```

vi interFoam.C

```
:47
#include "solidParticleCloud.H"

:63
solidParticleCloud particles(mesh);

:106
particles.move(g);
Info<< "Cloud size= "<< particles.size() <<endl;
runTime.write();
```

Compile the solver

wmake

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Goal: Inject 2 particles (P1 and P2).
We'll give in a dictionary (particleProperties):

- position (posP1 and posP2)
- diameter (Dp1 and Dp2)
- velocity (Up1 and Up2)
- time when injection starts and ends.

And the constructor needs to know

- position
- cell
- diameter (and not mass!)
- velocity

solidParticle.H

```
//- Construct from components
 inline solidParticle
  (
   const Cloud<solidParticle>& c,
   const vector& position,
   const label celli,
   const scalar m,
   const vector& U
  );
```

vi solidParticleCloud.C

```
mu_(dimensionedScalar(particleProperties_.lookup("mu")).value()),
posP1_(dimensionedVector(particleProperties_.lookup("posP1")).value()),
dP1_(dimensionedScalar(particleProperties_.lookup("dP1")).value()),
UP1_(dimensionedVector(particleProperties_.lookup("UP1")).value()),
posP2_(dimensionedVector(particleProperties_.lookup("posP2")).value()),
dP2_(dimensionedScalar(particleProperties_.lookup("dP2")).value()),
UP2_(dimensionedVector(particleProperties_.lookup("UP2")).value()),
tInjStart_(dimensionedScalar(particleProperties_.lookup("tInjStart")).value()),
tInjEnd_(dimensionedScalar(particleProperties_.lookup("tInjEnd")).value())
```

vi solidParticleCloud.H

```
scalar mu_;
vector posP1_;
scalar dP1_;
vector UP1_;
vector posP2_;
scalar dP2_;
vector UP2_;
scalar tInjStart_;
scalar tInjEnd_;
```

vi solidParticleCloud.C

```
// * * * * * * * * * * * * * * * Member Functions  * * * * * * * * * * * * * * //
 void Foam::solidParticleCloud::inject(solidParticle::trackData &td)
{
  label cellI=mesh_.findCell(td.spc().posP1_);
  solidParticle* ptr1= new solidParticle(*this,td.spc().posP1_,cellI,
   td.spc().dP1_,td.spc().UP1_);
  Cloud<solidParticle>::addParticle(ptr1);

  cellI=mesh_.findCell(td.spc().posP2_);
  solidParticle* ptr2= new solidParticle(*this,td.spc().posP2_,cellI,
   td.spc().dP2_,td.spc().UP2_);
  Cloud<solidParticle>::addParticle(ptr2);
}
```

In the function move

```
Cloud< solidParticle>::move(td);
 if(mesh_.time().value()> td.spc().tInjStart_ &&
      mesh_.time().value()< td.spc().tInjEnd_)
    {
     this->inject(td);
    }
```

vi solidParticleCloud.H

```
void move(const dimensionedVector& g);
//- Inject particles according to the dictionnary particleProperties
void inject(solidParticle::trackData &td);
```

- Compile the solver :

  wmake

- Go to the test case boxLPT directory :

  cd $WM_PROJECT_USER_DIR/run/boxLPT

- Have a look at the injector dictionary

  vi constant/particleProperties

```
rhop rhop [ 1 -3  0  0  0  0  0] 1000;
e    e    [ 0  0  0  0  0  0  0] 0.2;
mu   mu   [ 0  0  0  0  0  0  0] 0.02;
posP1 posP1 [ 0  1  0  0  0  0  0] (0.005 0.0 0.0125);
dP1 dP1 [ 0  1  0  0  0  0  0] 0.0002;
UP1 UP1 [ 0  1 -1   0  0  0  0] (-7.071 0 -7.071);
posP2 posP2 [ 0  1  0  0  0  0  0] (-0.0054 0.0 0.0125);
dP2 dP2 [ 0  1  0  0  0  0  0] 0.0002;
UP2 UP2 [ 0  1 -1   0  0  0  0] (7.071 0 -7.071);
tInjStart tInjStart [ 1 0   0  0  0  0  0] 0;
tInjEnd tInjEnd [ 1 0   0  0  0  0  0] 0.0000252;
```

- Run the solver

  myLPTVOF > log&

- Have a look at the log file to check if particles were injected.

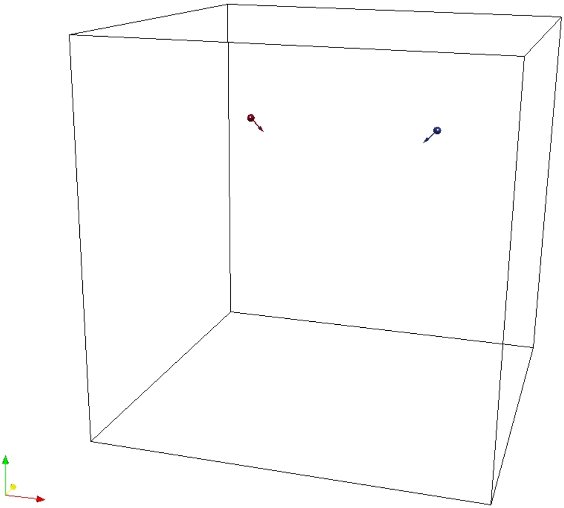
- Load the results in paraview

  touch boxLPT.foam
  paraview
  File Open boxLPT.foam

- Visualize the particles:

  Mesh regions: lagrangian/DefaultCloud
  Glyph: Type Sphere, Mode Scalar, Edit Set Scalar Factor 1

Add a particle injector



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   - Add a LPT solver to interFoam
   - Add a particle injector
   - **Add two-way coupling**
   - Add four-way coupling
     - A deterministic model for collision
     - Implementation in OpenFoam
     - The outcome of collision
     - Implementation in OpenFoam
   - Convert particle to VOF
     - Grid refinement
     - Set the volume fraction to 1 in the bottom region
     - Implement a algorithm which switch from LPT to VOF when the particle is close enough to a VOF interface

Two-way coupling: We want to account for the influence of the particles on the continuous phase, i.e. we add the source term S_p in the momentum equations for the mixture:

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = -\nabla p + \mu \nabla^2 \mathbf{U} + \rho \mathbf{g} - \mathbf{S_{st}} + \mathbf{S_P}.$$

$$\mathbf{S_P} = \frac{1}{V_{cell} \Delta t} \sum_P m_P((\mathbf{U_p})_{t_{out}} - (\mathbf{U_p})_{t_{in}})$$

$$\mathbf{S_P} = \frac{1}{V_{cell}\Delta t}\sum_P m_P((\mathbf{U_p})_{t_{out}} - (\mathbf{U_p})_{t_{in}})$$

vi solidParticle.C

```
scalar m=rhop*4/3*mathematicalConstant::pi*pow(d_/2,3);
vector oldMom=U_*m;
U_ = (U_ + dt*(Dc*Uc + (1.0 - rhoc/rhop)*td.g()))/(1.0 + dt*Dc);
vector newMom=U_*m;
td.spc().smom()[celli] += newMom-oldMom;
```

vi solidParticleCloud.C

```
mu_(dimensionedScalar(particleProperties_.lookup("mu")).value()),
smom_(mesh_.nCells(), vector::zero)

smom_=vector::zero;
solidParticle::trackData td(*this, rhoInterp, UInterp, nuInterp, g.value());
```

vi solidParticleCloud.H

```
// Private data
       ...
  scalar mu_;
  vectorField smom_;

inline scalar mu() const;
inline vectorField& smom();
inline const vectorField& smom() const;
inline tmp<volVectorField> momentumSource() const;
```

$$\mathbf{S_P} = \frac{1}{V_{cell}\Delta t}\sum_P m_P((\mathbf{U_p})_{t_{out}} - (\mathbf{U_p})_{t_{in}})$$

vi solidParticleCloudI.H

```
inline tmp<volVectorField> solidParticleCloud::momentumSource() const
{
    tmp<volVectorField> tsource
    (
        new volVectorField
        (
            IOobject
            (
                "smom",
                mesh_.time().timeName(),
                mesh_,
                IOobject::NO_READ,
                IOobject::NO_WRITE
            ),
            mesh_,
            dimensionedVector
            (
                "zero",
                dimensionSet(1, -2, -2, 0, 0),
                vector::zero
            )
        )
    );
    tsource().internalField() = smom_/(mesh_.time().deltaT().value()*mesh_.V());
    return tsource;
}
```

```
inline Foam::vectorField& Foam::solidParticleCloud::smom()
 {
     return smom_;
 }

inline const Foam::vectorField& Foam::solidParticleCloud::smom() const
 {
     return smom_;
 }
```

start the file with

```
 namespace Foam
{
```

end the file with

```
} // End namespace Foam
```

Add the source term in **UEqn.H**

```
if (momentumPredictor)

        solve
        (
            UEqn
         ==
            fvc::reconstruct
            (
                fvc::interpolate(rho)*(g & vofMesh.Sf())
              + (
                    fvc::interpolate(interface.sigmaK())*fvc::snGrad(alpha1)
                  - fvc::snGrad(p_rgh)
                ) * vofMesh.magSf()
            )
            +particles.momentumSource()
        );
```

- Compile the solver :

  wmake

- Go to the test case boxLPT directory :

  cd $WM_PROJECT_USER_DIR/run/boxLPT

- Run the solver

  myLPTVOF > log&

- Load the results in paraview

  paraview

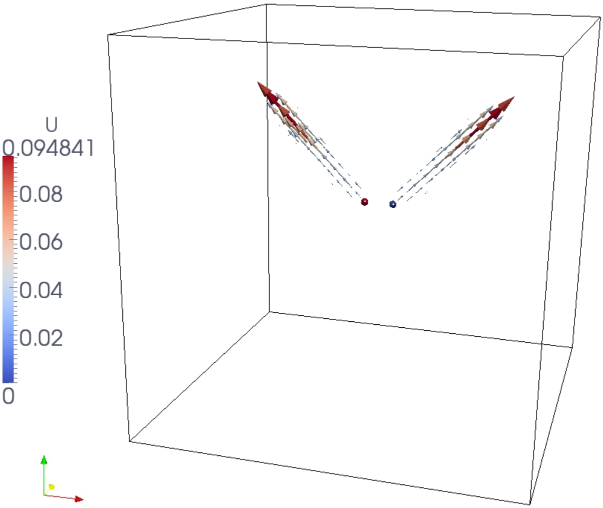
- Visualize the particles:

  Mesh regions: lagrangian/DefaultCloud
  Glyph: Type Sphere, Mode Scalar, Edit Set Scalar Factor 1

- Plot the vectors of the continuous phase in the y-plane

  Mesh regions: internalMesh
  Slice: Y Normal
  Glyph: Type Arrow, Mode Vector, Edit Set Scalar Factor 0.03, No Mask Points, No Random Mode

Add two-way coupling



Four-way coupling: particle-particle collision.

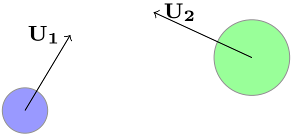
In OpenFoam, there are 2 models available for modeling particle collision:

vi $FOAM_SRC/lagrangian/dieselSpray/spraySubModels/collisionModel

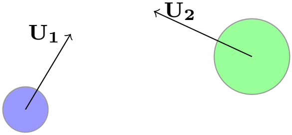
- O'rourke model: collision occurs with a certain probability if 2 particles are in the same cell.
- Trajectory model: collision occurs with a ceratin probability if 2 particles are close enough and if they move toward each other.

We want a deterministic model. So we derive one and implement it.

We want to determine when collision occurs between particles P_1 and P_2.

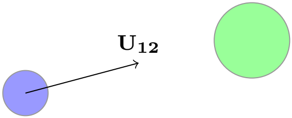


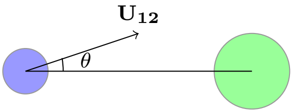
We want to determine when collision occurs between particles P_1 and P_2.



Let particle 2 be the new coordinate reference system,

- Particle 2 has a velocity $\mathbf{U_{22}} = 0$
- Particle 1 has a velocity $\mathbf{U_{12}} = \mathbf{U_1} - \mathbf{U_2}$



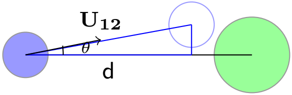


The angle θ is the angle between line (1,2) and $\mathbf{U_{12}}$:

$$cos\theta = \frac{\mathbf{U_{12}}}{|\mathbf{U_{12}}|} \cdot \frac{\mathbf{posP_2} - \mathbf{posP_1}}{|\mathbf{posP_2} - \mathbf{posP_1}|}$$

There exists a critical value θ_c such that if $\theta < \theta_c$ then collision is possible.

Let's consider the case $\theta < \theta_c$.



The distance d is the projection on line (1,2) of the distance travelled during the time step dt :

$$d = |\mathbf{U_{12}}| cos\theta dt$$

Then the particle 1 should travel long enough during this time step. So there exists also a critical distance d_c such that if $d > d_c$ then collision occurs.

We create the file **myCM.H**

```
//evaluate thetac
vector p = p2().position() - p1().position();
scalar dist = mag(p);
scalar sumR = (p1().d() + p2().d())/2.0;
scalar thetac = atan(sumR/ sqrt(sqr(dist)+sqr(sumR)));
// evaluate theta
vector v1 = p1().U();
vector v2 = p2().U();
vector vRel = v1 - v2;
scalar magVRel = mag(vRel);
scalar theta = acos( (vRel/(magVRel+SMALL)) & (p/(dist+SMALL)) );
if ( theta <thetac)
{
 Info<< "theta smaller than thetac"<<endl;
 // evaluate dcoll
 scalar dt = mesh_.time().deltaT().value();
 scalar vcoll = vRel & (p/(dist+SMALL));
 scalar dcoll = vcoll * dt;
 // evaluate dcollc
 scalar denom=1.0+sqr(tan(theta));
 scalar dcollc = 2* dist -2* sqrt(sqr(dist) - denom*(sqr(dist)-sqr(sumR)));
 dcollc /= (2*denom);
 if (dcoll  > dcollc)
 {
  collision=true;
  Info<<"collision occurs"<<endl;
 } // if - collision distance
} // if - collision angle
```

vi interFoam.C

```
Info<< "Time = " << runTime.timeName() << nl << endl;
particles.checkCo();
```

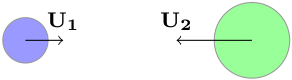
vi solidparticleCloud.H

```
void move(const dimensionedVector& g);
//- Check if there will be collision and update velocities
void checkCo();
```

vi solidparticleCloud.C

```
 void Foam::solidParticleCloud::checkCo()
{
   if ((*this).size() < 2)
    {
       return;
    }
    Cloud<solidParticle>::iterator secondP = (*this).begin();
    ++secondP;
    Cloud<solidParticle>::iterator p1 = secondP;
    while (p1 != (*this).end())
    {
      Cloud<solidParticle>::iterator p2 = (*this).begin();
      while (p2 != p1)
        {
          bool collision=false;
          #            include "myCM.H"
      if (collision)
          {
           p1.U() = ??;
           p2.U() = ??;
           Info<< "new velocities "<< p1().U() << p2().U()<<endl;
         }
         ++p2;
        } // end - inner loop
      ++p1;
    } // end - outer loop
}
```

1D collision



Conservation of momentum

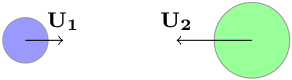
$$m_1\mathbf{U_1} + m_2\mathbf{U_2} = m_1\mathbf{U_1'} + m_2\mathbf{U_2'} \tag{1}$$

Coefficient of restitution (loss of kinetic energy) ϵ

$$\epsilon = \frac{\mathbf{U_2'} - \mathbf{U_1'}}{\mathbf{U_1} - \mathbf{U_2}} \tag{2}$$

Eq(1): $\mathbf{U_1'} = \frac{m_1\mathbf{U_1} + m_2\mathbf{U_2} - m_2\mathbf{U_2'}}{m_1}$
Eq(2): $\mathbf{U_2'} = \epsilon(\mathbf{U_1} - \mathbf{U_2}) + \mathbf{U_1'}$

1D collision



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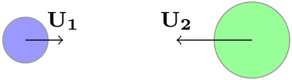
Eq(1): $\mathbf{U_1'} = \frac{m_1\mathbf{U_1}+m_2\mathbf{U_2}-m_2\mathbf{U_2'}}{m_1}$
Eq(2): $\mathbf{U_2'} = \epsilon(\mathbf{U_1} - \mathbf{U_2}) + \mathbf{U_1'}$

$$\mathbf{U_1'} = \frac{m_1\mathbf{U_1} + m_2\mathbf{U_2} - m_2\epsilon(\mathbf{U_1} - \mathbf{U_2})}{m_1 + m_2}$$

1D collision



Conservation of momentum

$$m_1\mathbf{U_1} + m_2\mathbf{U_2} = m_1\mathbf{U_1'} + m_2\mathbf{U_2'} \tag{1}$$

Coefficient of restitution (loss of kinetic energy) ϵ

$$\epsilon = \frac{\mathbf{U_2'} - \mathbf{U_1'}}{\mathbf{U_1} - \mathbf{U_2}} \tag{2}$$

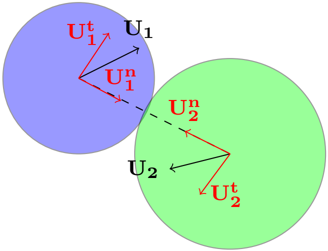
Eq(1): $\mathbf{U_1'} = \frac{m_1\mathbf{U_1} + m_2\mathbf{U_2} - m_2\mathbf{U_2'}}{m_1}$
Eq(2): $\mathbf{U_2'} = \epsilon(\mathbf{U_1} - \mathbf{U_2}) + \mathbf{U_1'}$

$$\mathbf{U_1'} = \frac{m_1\mathbf{U_1} + m_2\mathbf{U_2} - m_2\epsilon(\mathbf{U_1} - \mathbf{U_2})}{m_1 + m_2}$$

Similarly,

$$\mathbf{U_2'} = \frac{m_1\mathbf{U_1} + m_2\mathbf{U_2} - m_1\epsilon(\mathbf{U_2} - \mathbf{U_1})}{m_1 + m_2}$$

2D collision



The velocities are decomposed into normal and tangential component, $\mathbf{U_i} = \mathbf{U_i^n} + \mathbf{U_i^t}$
The unit normal vector is $\mathbf{n_{12}} = \frac{\mathbf{x_2} - \mathbf{x_1}}{|\mathbf{x_2} - \mathbf{x_1}|}$ so $\mathbf{U_i^n} = (\mathbf{U_i} \& \mathbf{n_{12}}) \cdot \mathbf{n_{12}}$
The normal component changes according to the expression derived for 1D collision.

The tangential component is unchanged (friction neglected).

In **solidparticleCloud.C**

```
p1.U() = ??;
p2.U() = ??;
```

become

```
Info<< "Velocities before collision: "<< p1().U() <<p2().U()<<endl;
vector p = p2().position() - p1().position();
vector n12=p/mag(p);
scalar v1n=p1().U() & n12;
vector v1t=p1().U() - v1n*n12 ;
scalar v2n=p2().U() & n12;
vector v2t=p2().U() - v2n*n12 ;
scalar COR=0.8;
scalar m1 = rhop()*mathematicalConstant::pi / 6.0*pow(p1().d(),3);
scalar m2 = rhop()*mathematicalConstant::pi / 6.0*pow(p2().d(),3);
scalar mrn = m1*v1n + m2*v2n;
scalar vnRel = v1n - v2n;
 p1().U() = v1t+ ((mrn - COR* m2*vnRel)/(m1+m2))*n12;
 p2().U() = v2t+ ((mrn + COR* m1*vnRel)/(m1+m2))*n12;
Info<< "new velocities "<< p1().U() << " and "<<p2().U()<<endl;
```

Compile the solver :

wmake

```
error: passing ‘const Foam::vector’ as ‘this’ argument of
‘Foam::Vector<double>& Foam::Vector<double>::operator=
(const Foam::Vector<double>&)’ discards qualifiers
```

Debug 1

```
p1().U() == ...
p2().U() == ...
```

Compile the solver :

wmake

It gives no error message.
Run the solver with the case boxLPT :

cd $WM_PROJECT_USER_DIR/run/boxLPT
myLPTVOF > log&

Have a look at the velocities after collision in the log file ...

Debug 2

U is a member of the class solidParticle, which has a **const** qualification, and therefore cannot be modified within solidParticleCloud!

We want to change the value of U after a collision .

So we use the C++ process **const_cast** which removes the const qualification of an object. It is called "casting away constness".

```
solidParticle& changep1= const_cast<solidParticle&>(p1());
solidParticle& changep2= const_cast<solidParticle&>(p2());
changep1.U_ = ...
changep2.U_ = ...
```

Compile the solver :

wmake

```
error: 'Foam::vector Foam::solidParticle::U_' is private
```

Debug 3

vi solidParticle.H

```
class solidParticle
:
    public Particle<solidParticle>
{
    // Private member data
        //- Diameter
        scalar d_;
        //- Velocity of particle
        vector U_;
public:
    friend class Cloud<solidParticle>;
    friend class solidParticleCloud;
```

Compile the solver :

wmake

It gives no error message.
Run the solver with the case boxLPT

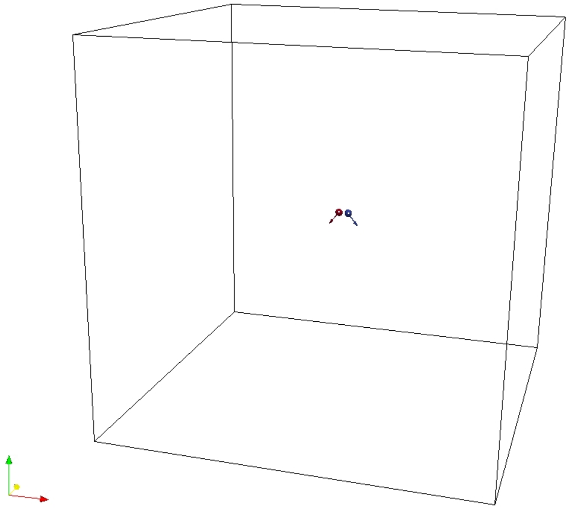
- **cd $WM_PROJECT_USER_DIR/run/boxLPT**
- Run the solver

  myLPTVOF >log&

- Have a look at the velocities after collision in the log file
- Visualize the particles:

  Mesh regions: lagrangian/DefaultCloud Glyph: Type Sphere, Mode Scalar, Edit Set Scalar Factor 1 Colored by origId

Add four-way coupling



1 Multiphase flow methods
- VOF
- VOF in OpenFOAM
- LPT
- LPT in OpenFOAM

2 Tutorial
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Last task for today... We'll add water in the bottom of the box. We want to switch to VOF approach when the droplets are in contact with the free surface.

- We will have a coarse mesh when we track the droplet with LPT (the cell must be larger than the particle because the particle is modeled as a point source)
- and a fine mesh to describe the free surface and underneath (because it is a requirement for accuracy with the VOF method).

So we need to

- refine the grid in a region of the domain (refineMesh -dict)
- set alpha to 1 in this region (setField)
- implement a algorithm which switch from LPT to VOF when the particle is close enough to a VOF interface

```
cd $WM_PROJECT_USER_DIR/run/boxLPT
cp $WM_PROJECT_DIR/applications/utilities/mesh/manipulation/
      refineMesh/refineMeshDict system/

cp $WM_PROJECT_DIR/applications/utilities/mesh/manipulation/
      cellSet/cellSetDict system/
```

Define a set of cell to be refined: in system/cellSetDict, topoSetSource, keep only

```
boxToCell
   {
      box   (-0.01 -0.01 0) (0.01 0.01 0.005);
   }
```

Create the set of cells c0

cellSet

Refine the cells listed in the set c0

refineMesh -dict

The refined mesh is written in the time directory 2.5e-05. We have to move it:

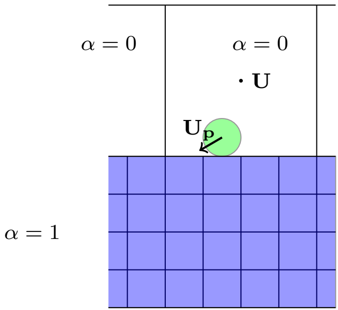
```
mv constant/polyMesh constant/polyMesh_br
mv 2.5e-05/polyMesh constant/
rm -r 2.5e-05/
```

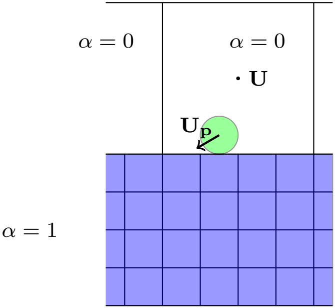
```
cp $WM_PROJECT_DIR/applications/utilities/preProcessing/
    setFields/setFieldsDict
```

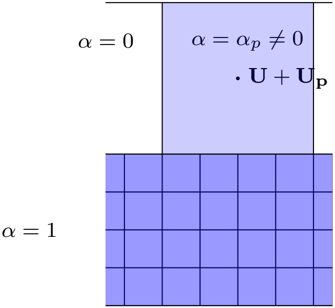
vi setFieldsDict

```
defaultFieldValues
(
    volScalarFieldValue alpha1 0
);
regions
(
    boxToCell
    {
        box (-0.01 -0.01 0) (0.01 0.01 0.005);
        fieldValues
        (
            volScalarFieldValue alpha1 1
        );
    }
);
```

setFields


$\alpha = 0$
$\alpha = 0$
$\cdot\, \mathbf{U}$
$\mathbf{U_P}$
$\alpha = 1$


$\alpha = 0$
$\alpha = 0$
$\mathbf{U}$
$\mathbf{U_p}$
$\alpha = 1$


$\alpha = 0$
$\alpha = \alpha_p \neq 0$
$\mathbf{U} + \mathbf{U_p}$
$\alpha = 1$

The algorithm is implemented in the file **LPTtoVOF.H**.
This file must be called in **solidParticle.C**, in the function move :

```
     #include "LPTtoVOF.H"
    }
    return td.keepParticle;
}
```

- We want to change the value of alpha1 and U in some cells, so we create a function addToAlpha and addToU, almost as we did for adding a source term in the momentum equation.
- We need access to the cell value of the eulerian volScalarField alpha1, ie alpha1 interpolated at the cell center

vi solidParticle.H

```
#include "interpolationCellPoint.H"
 #include "interpolationCell.H"

class trackData
    {
        //- Reference to the cloud containing this particle
        solidParticleCloud& spc_;
        // Interpolators for continuous phase fields
            const interpolationCellPoint<scalar>& rhoInterp_;
            const interpolationCellPoint<vector>& UInterp_;
            const interpolationCellPoint<scalar>& nuInterp_;
            const interpolationCell<scalar>&  alpha1Interp_;
        // Constructors
            inline trackData
            (
                solidParticleCloud& spc,
                const interpolationCellPoint<scalar>& rhoInterp,
                const interpolationCellPoint<vector>& UInterp,
                const interpolationCellPoint<scalar>& nuInterp,
                const interpolationCell<scalar>& alpha1Interp,
                const vector& g
            );
        // Member function
            inline solidParticleCloud& spc();
            inline const interpolationCellPoint<scalar>& rhoInterp() const;
            inline const interpolationCellPoint<vector>& UInterp() const;
            inline const interpolationCellPoint<scalar>& nuInterp() const;
            inline const interpolationCell<scalar>& alpha1Interp() const;
```

vi solidParticleI.H

```
inline Foam::solidParticle::trackData::trackData
(
    solidParticleCloud& spc,
    const interpolationCellPoint<scalar>& rhoInterp,
    const interpolationCellPoint<vector>& UInterp,
    const interpolationCellPoint<scalar>& nuInterp,
    const interpolationCell<scalar>& alpha1Interp,
    const vector& g
)
:
    spc_(spc),
    rhoInterp_(rhoInterp),
    UInterp_(UInterp),
    nuInterp_(nuInterp),
    alpha1Interp_(alpha1Interp),
    g_(g)

inline const Foam::interpolationCellPoint<Foam::scalar>&
Foam::solidParticle::trackData::nuInterp() const

    return nuInterp_;

inline const Foam::interpolationCell<Foam::scalar>&
Foam::solidParticle::trackData::alpha1Interp() const
{
    return alpha1Interp_;
}
```

vi solidParticleCloud.C

```
smom_(mesh_.nCells(), vector::zero),
correctalpha1_(mesh_.nCells(), 0),
correctU_(mesh_.nCells(), vector::zero),

const volScalarField& nu = vofMesh_.lookupObject<const volScalarField>("nu");
const volScalarField& alpha1 = mesh_.lookupObject<const volScalarField>("alpha1");

interpolationCellPoint<scalar> nuInterp(nu);
interpolationCell<scalar> alpha1Interp(alpha1);

smom_=vector::zero;
correctalpha1_=0;
correctU_=vector::zero;
solidParticle::trackData td(*this, rhoInterp, UInterp, nuInterp,alpha1Interp,  g.value());
```

vi solidParticleCloud.H

```
vectorField smom_;
scalarField correctalpha1_;
vectorField correctU_

inline tmp<volVectorField> momentumSource() const;
inline scalarField& correctalpha1();
inline const scalarField& correctalpha1() const;
inline tmp<volScalarField> AddTOAlpha() const;
inline vectorField& correctU();
inline const vectorField& correctU() const;
inline tmp<volVectorField> AddToU() const;
```

vi solidParticleCloudI.H

```
inline tmp<volScalarField> solidParticleCloud::AddTOAlpha() const
{
    tmp<volScalarField> alphasource
    (
        new volScalarField
        (
            IOobject
            (
                "correctalpha1",
                mesh_.time().timeName(),
                mesh_,
                IOobject::NO_READ,
                IOobject::NO_WRITE
            ),
            mesh_,
            dimensionedScalar
            (
                "zero",
                dimensionSet(0,0 , 0, 0, 0),
                0
            )
        )
    );
    alphasource().internalField() = correctalpha1_;
    return alphasource;
}
```

vi solidParticleCloudI.H

```
inline tmp<volVectorField> solidParticleCloud::AddToU() const
{
    tmp<volVectorField> Usource
    (
        new volVectorField
        (
            IOobject
            (
                "correctU",
                mesh_.time().timeName(),
                mesh_,
                IOobject::NO_READ,
                IOobject::NO_WRITE
            ),
            mesh_,
            dimensionedVector
            (
                "correctU",
                dimensionSet(0, 1, -1, 0, 0),
                vector(0,0,0)
            )
        )
    );
    Usource().internalField() = correctU_;
    return Usource;
}
```

```
inline Foam::scalarField& Foam::solidParticleCloud::correctalpha1()
 {
     return correctalpha1_;
 }

inline const Foam::scalarField& Foam::solidParticleCloud::correctalpha1() const
 {
     return correctalpha1_;
 }

inline Foam::vectorField& Foam::solidParticleCloud::correctU()
 {
     return correctU_;
 }

inline const Foam::vectorField& Foam::solidParticleCloud::correctU() const
 {
     return correctU_;
 }
```

vi interFoam.C

```
particles.move(g);
particles.checkCo();
alpha1 += particles.AddTOAlpha();
U += particles.AddToU();
runTime.write();
```

- Compile the solver :

  wmake

- Go to the test case boxLPT directory :

  cd $WM_PROJECT_USER_DIR/run/boxLPT

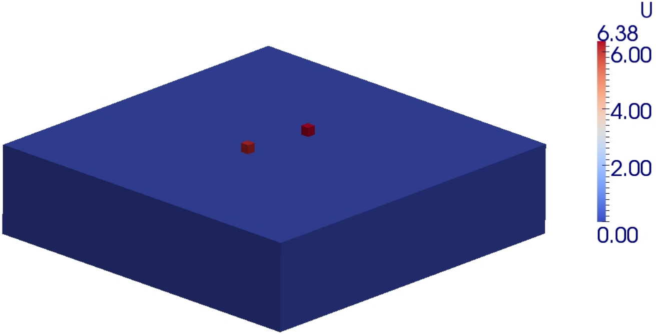
- Run the solver

  myLPTVOF > log&

- Load the results in paraview

  paraview

- Visualize the particles and then the cells with $\alpha > 0.03$ at t=0.001075.


U
6.38
6.00
4.00
2.00
0.00