OpenFOAMを用いた hydrothermal wave現象についての数値解析

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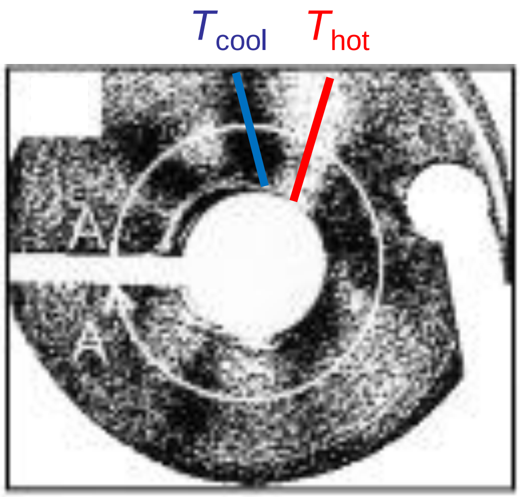
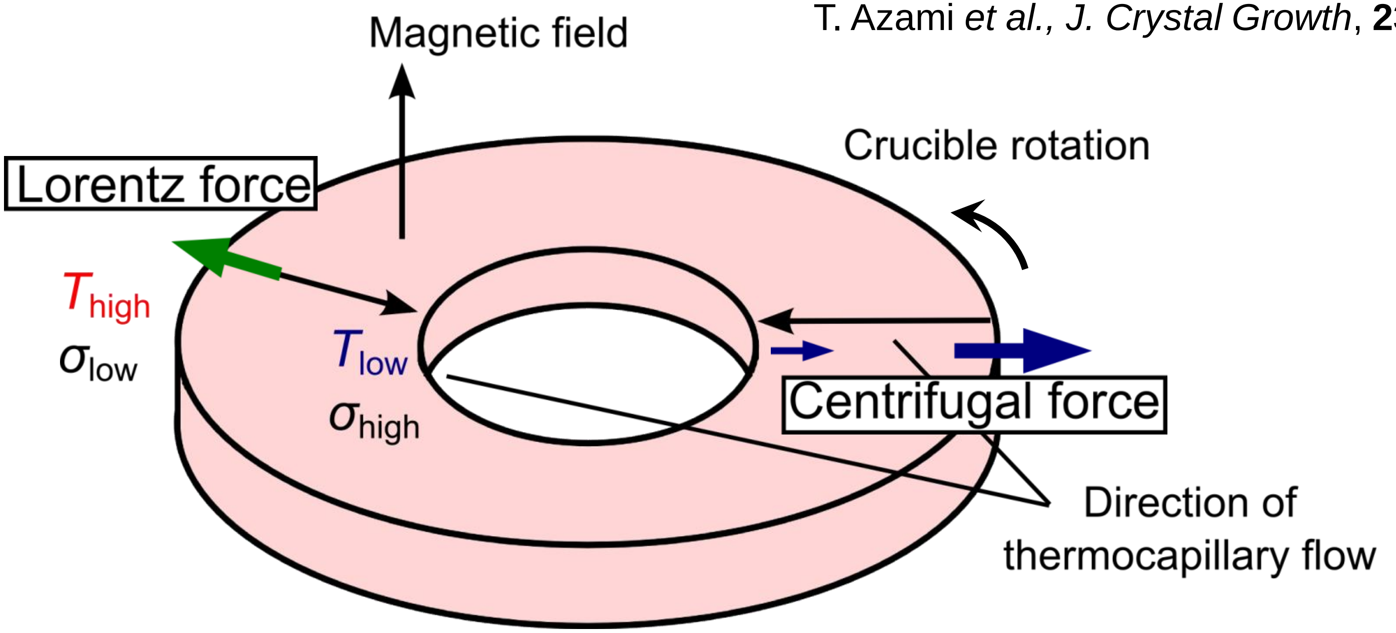
Introduction

- *Hydrothermal wave (HTW)* is observed at the final stage of Czochralski process.
  - Marangoni convection
  - Unsteady thermocapillary flow



T. Azami *et al., J. Crystal Growth*, **233**(2001).



Marangoni effect $\mu \frac{\partial \mathbf{v}}{\partial \mathbf{n}} = \sigma_T \nabla T$

Numerical conditions

Governing equations

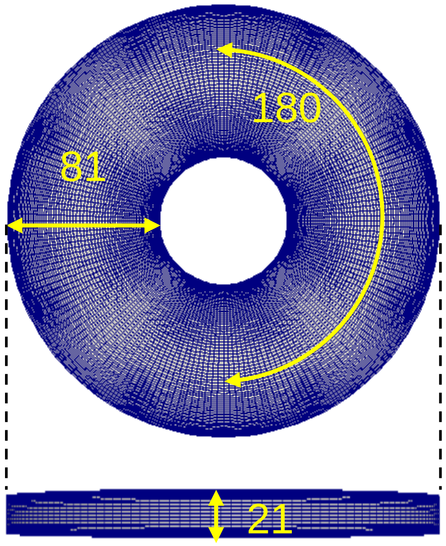
Continuity: $\nabla \cdot \mathbf{v} = 0$

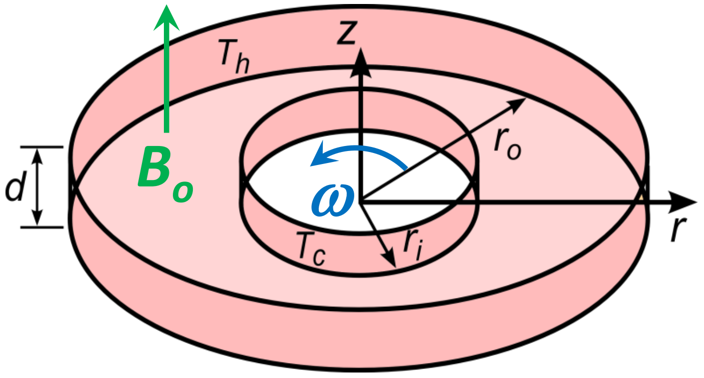
Navier-Stokes: $\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} + \mathbf{F}$

Energy: $\frac{\partial T}{\partial t} + \mathbf{v} \nabla T = \alpha \nabla^2 T$

Induced equation: $\frac{\partial \boldsymbol{B}}{\partial t} = \frac{1}{\sigma \mu} \nabla^2 \mathbf{B} + \nabla \times (\mathbf{v} \times \mathbf{B})$

Lorentz Force: $\mathbf{F} = \frac{1}{\mu} (\nabla \times \mathbf{B}) \times \mathbf{B}$





Parameters

Parameter	Value
Marangoni number (*Ma*)	2.91×10^3
Prandtl number (*Pr*)	1.09×10^{-2}
Rayleigh number	0(No gravity condition)
Magnetic flux density (B_0)	0, 39.5, 52.6, 132 mT
Hartmann number (*Ha*)	0, 7.5, 10, 25
Rotation speed (ω)	0, 1/60, 2/60, 5/60 s^{-1}
Rotational Reynolds number (Re_ω)	0, 464, 927, 2318

- Changing "icoFoam" solver to consider the effect of temperature and magnetic flux.

Numerical scheme

- Finite volume method
- PISO algorithm

Assumption

- No gravity condition
- Physical properties of silicon melt

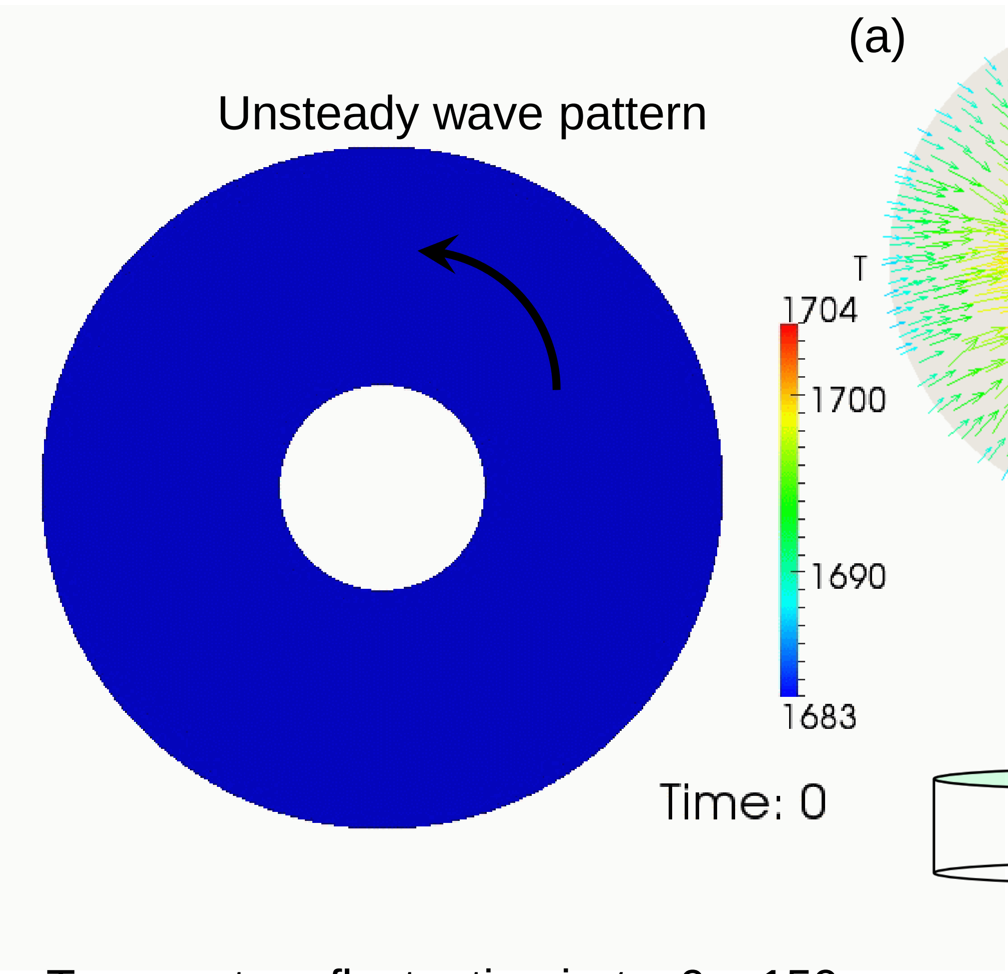
Boundary condition

- No-Slip (wall, bottom)
- Free surface (top)

Discretization

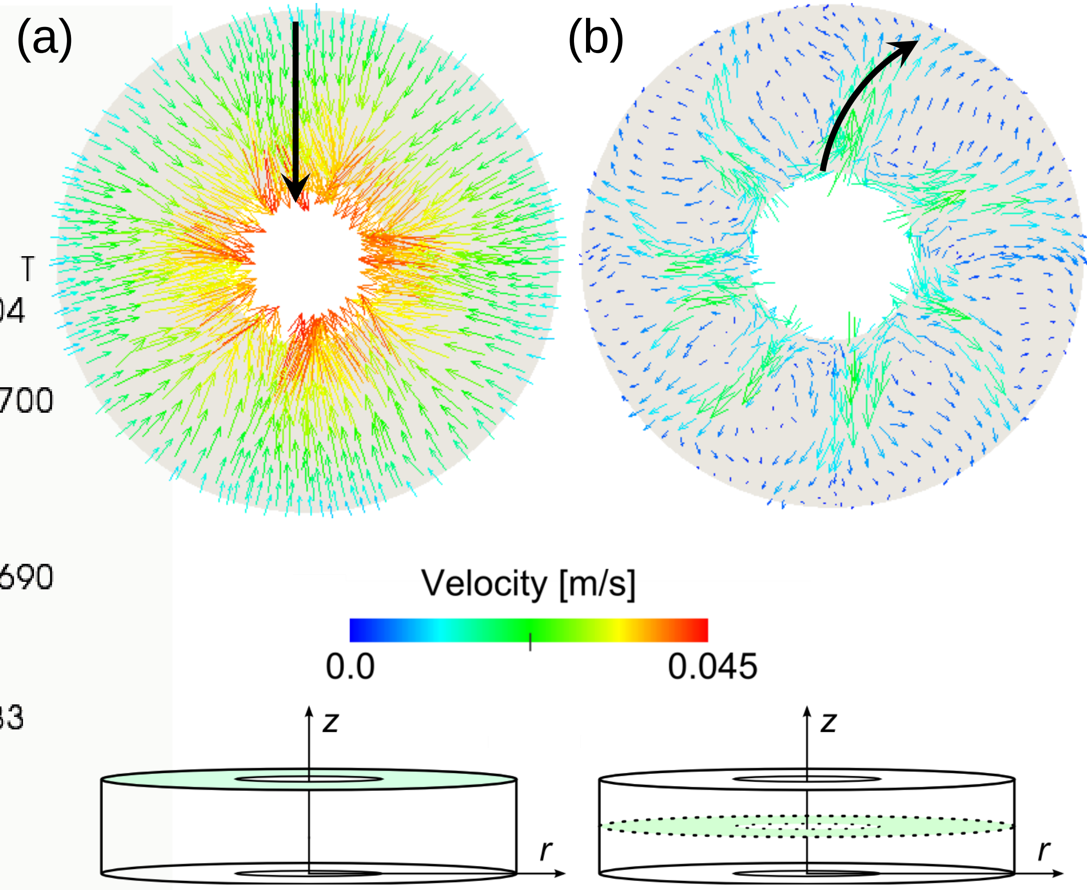
- Quick (divSchemes)
- Linear (Others)

Numerical results without external force



Temperature fluctuation in t = 0 – 150 s

at Ha = 0 and ω = 0 s^{-1}.



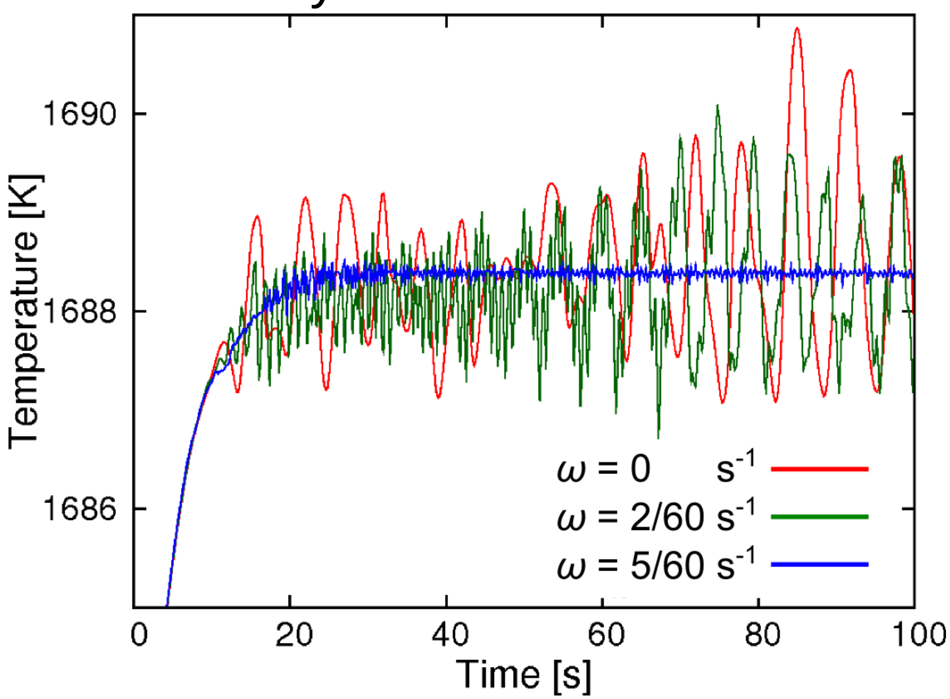
Velocity vector at t = 150 s

at Ha = 0 and ω = 0 s^{-1},

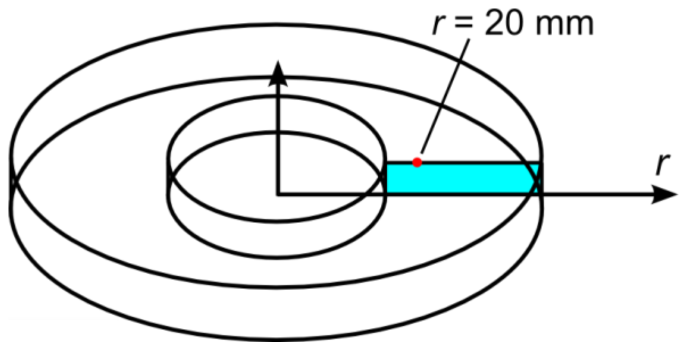
(a) d = 3 cm (b) d = 1.5 cm.

Effect of crucible rotation or magnetic field

Only crucible rotation



Time development of surface temperature



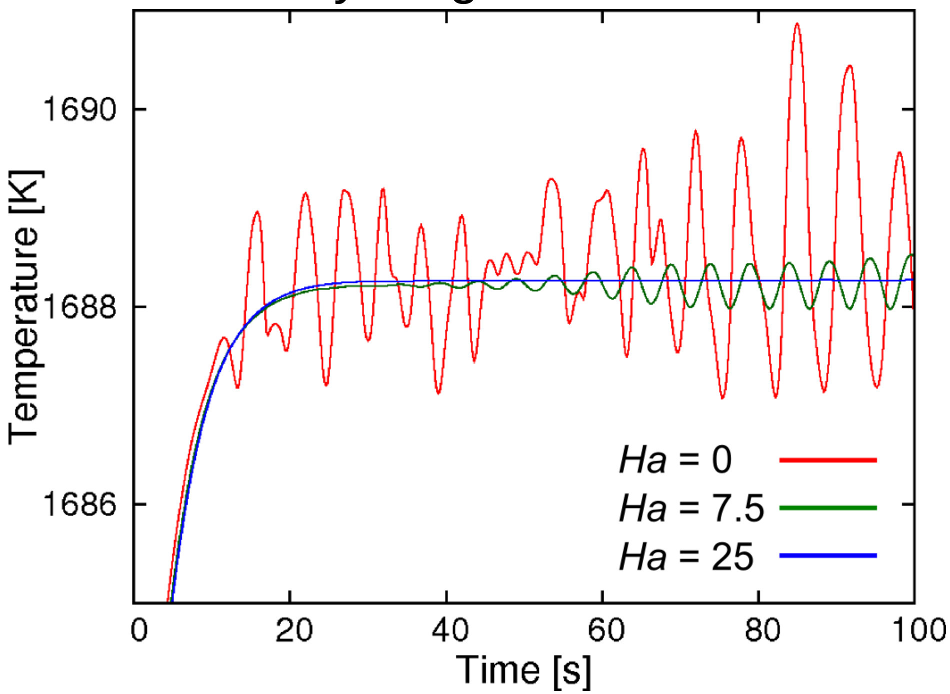
../system/controlDict

```
functions
(
    probes
    {
        type            probes;
        functionObjectLibs ("libsampling.so");
        enabled         true;
        outputControl   timeStep;
        outputInterval  50;
        probeLocations
        (
            (0.020 0.0 0.003)
         );

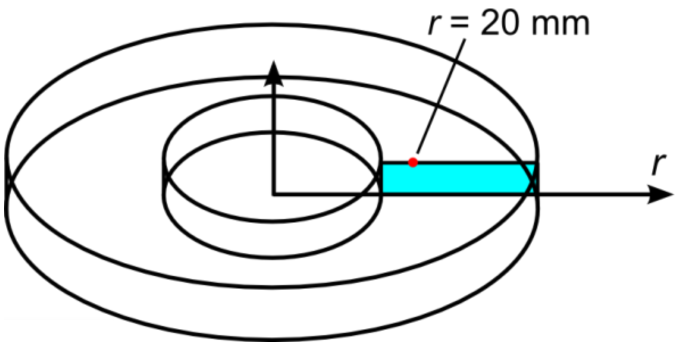
        fields
        (
            p
            U
            T
        );
    }
);
```

Effect of crucible rotation or magnetic field

Only magnetic field



Time development of surface temperature



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        (
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            T
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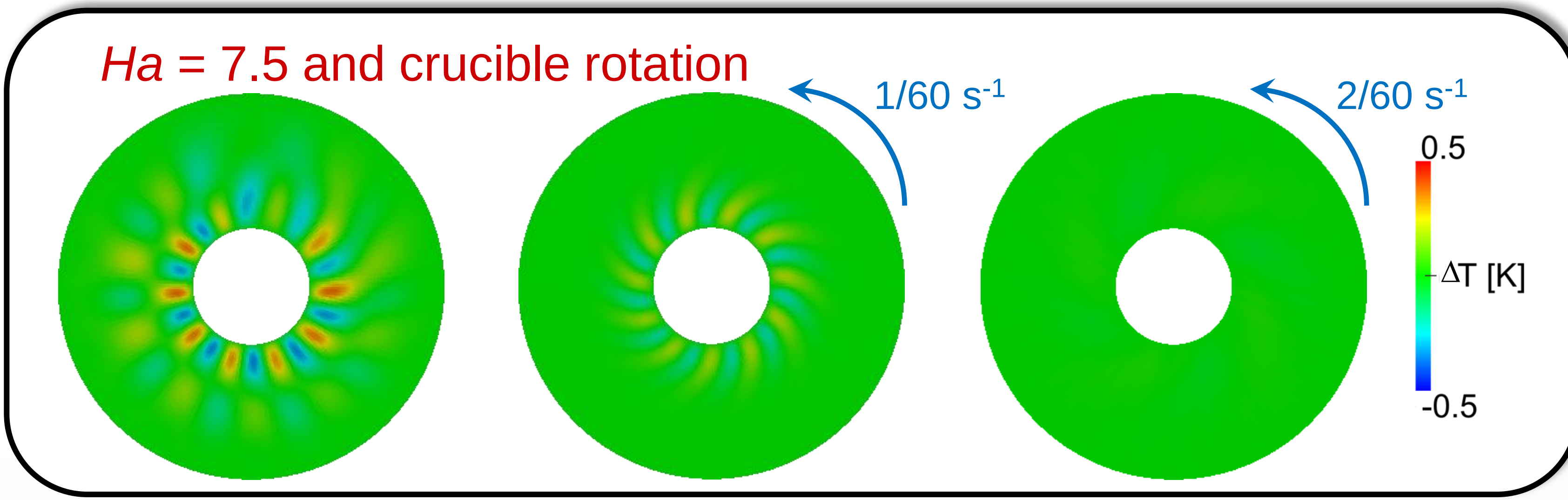
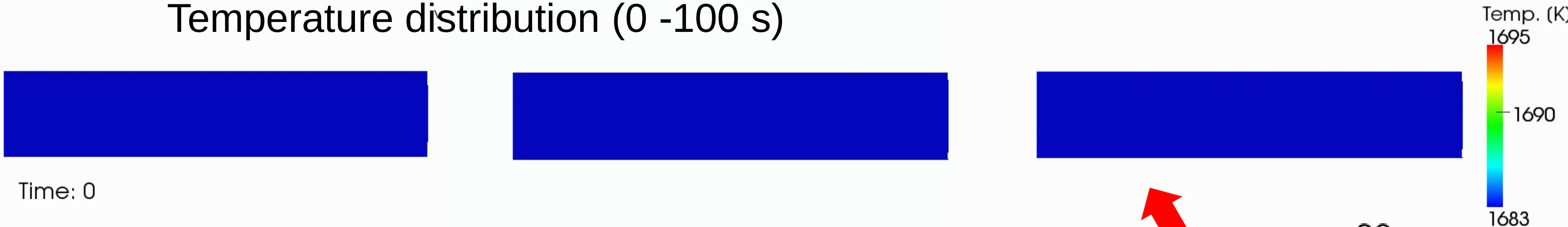
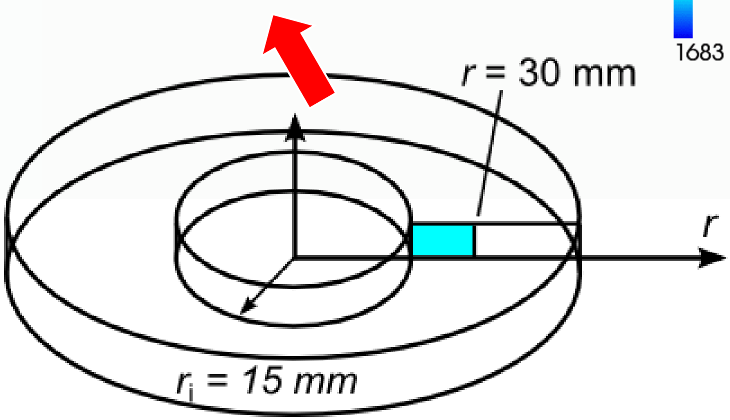
    }
);
```

Applying rotation and magnetic field simultaneously



Temperature distribution (0 -100 s)

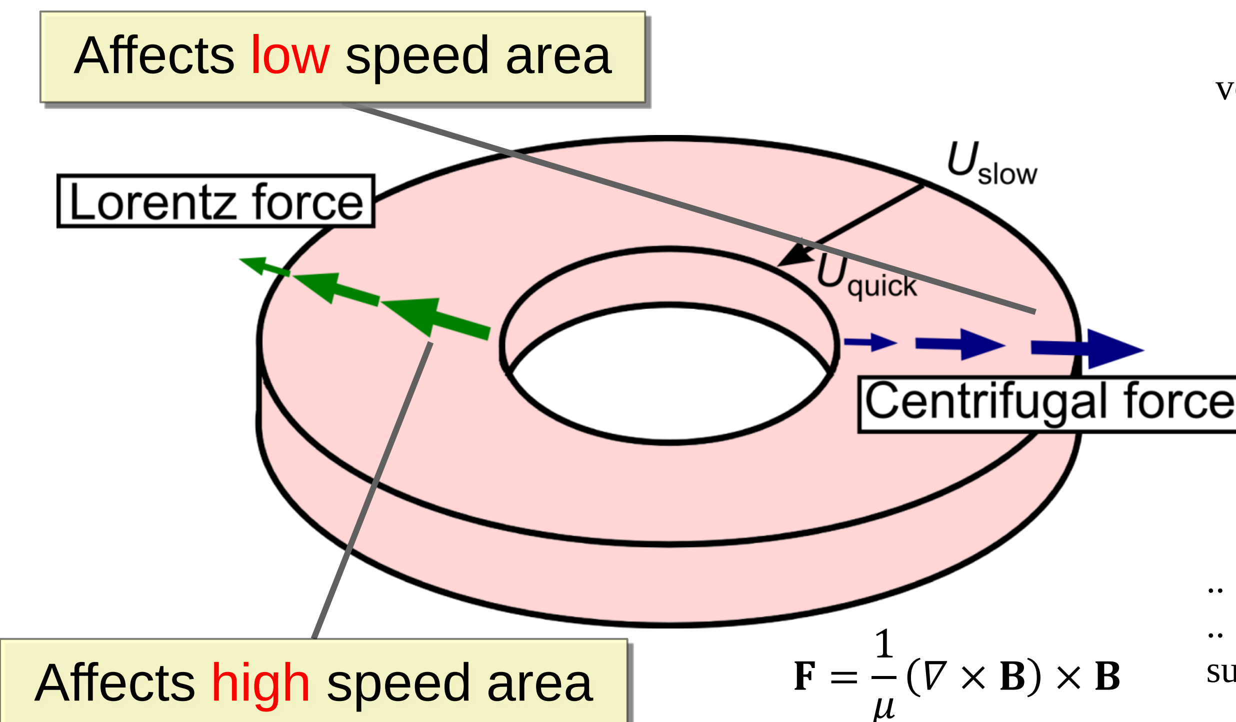




Steady flow pattern appeared at
Ha = 7.5 and ω = 2/60 s^{-1} conditions.

Total force both Lorentz and centrifugal force

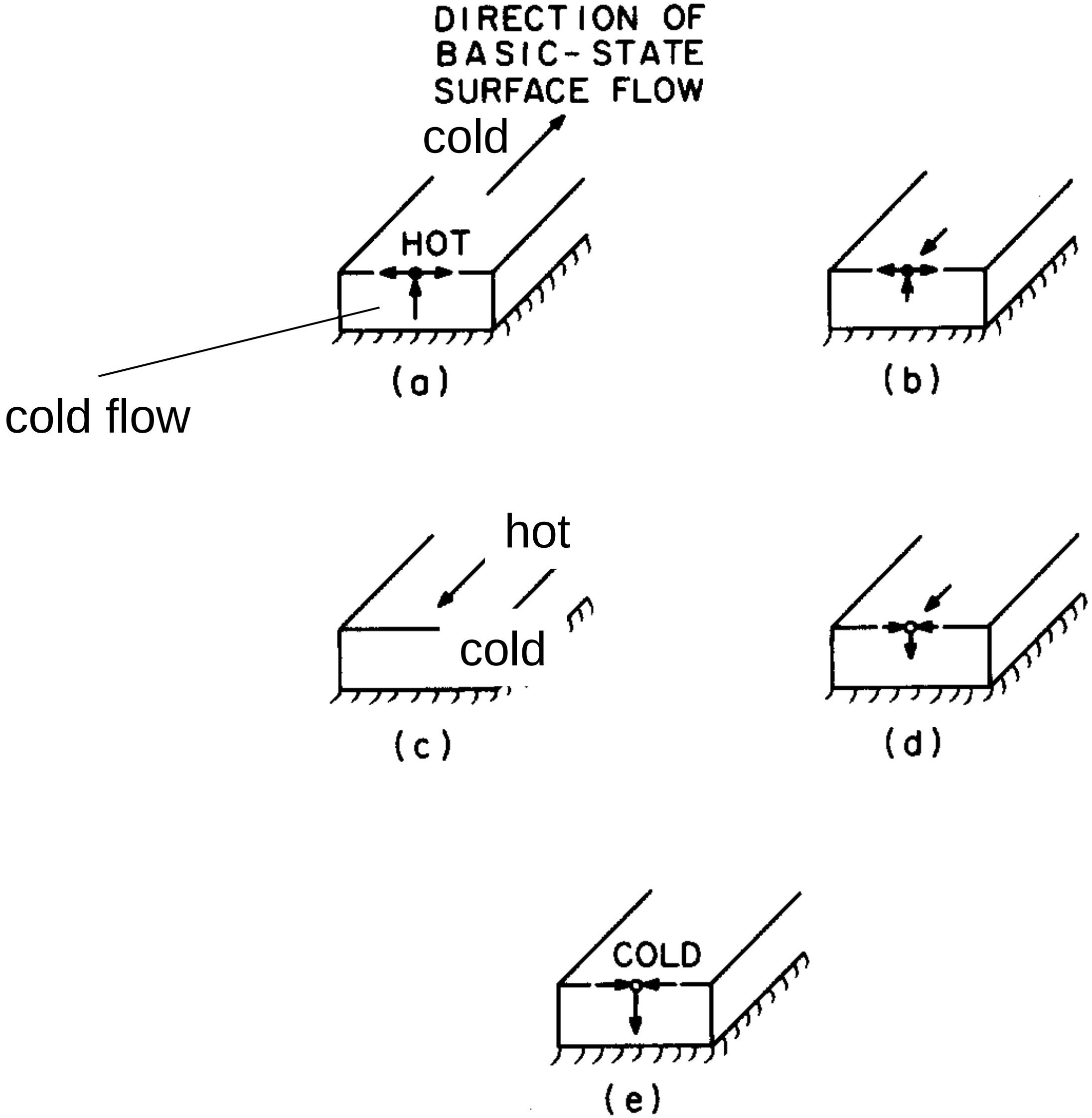
Conditions	Lorentz force [10^{-4} N]	Centrifugal force [10^{-4} N]	Total [10^{-4} N]	Results
Ha = 7.5	1.412	0	1.412	HTW
Ha = 10	2.124	0	*2.124*	*2D flow*
ω = 5/60 s^{-1}	0	5.297	*5.297*	*HTW*
Ha = 7.5, ω = 1/60 s^{-1}	1.416	0.212	1.628	HTW
Ha = 7.5, ω = 2/60 s^{-1}	1.419	0.848	*2.267*	*2D flow*



$$\mathbf{F} = \frac{1}{\mu}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

```
volVectorField Lorentz
    (
        IOobject
        (
            "Lorentz",
            runTime.timeName(),
            mesh,
            IOobject::NO_READ
        ),
        (1/mu)*fvc::curl(B)^B
    );
..
..
sum(magLorentz * mag(mesh.V())).value()
```

Mechanism of HTW

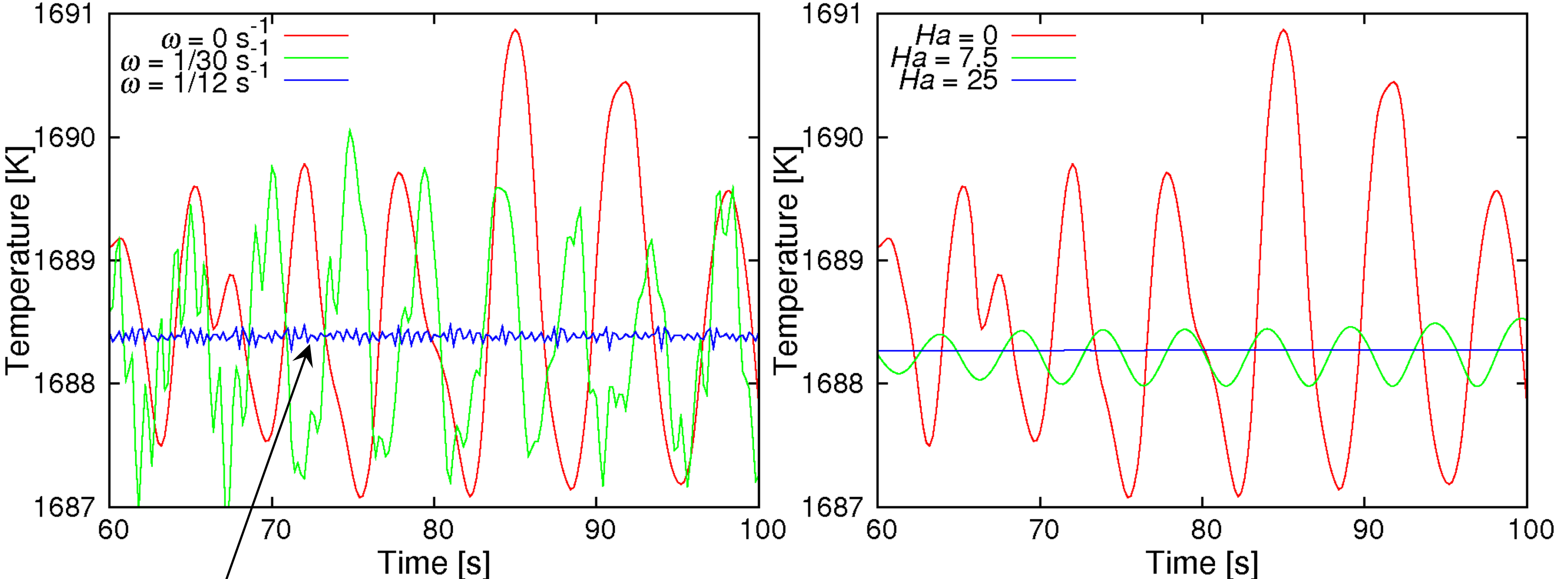


M. K. Smith, *Phys. Fluids,* **29**, 3182-3186 (1986).

Applying crucible rotation or magnetic fields only

Crucible rotation only

Magnetic fields only

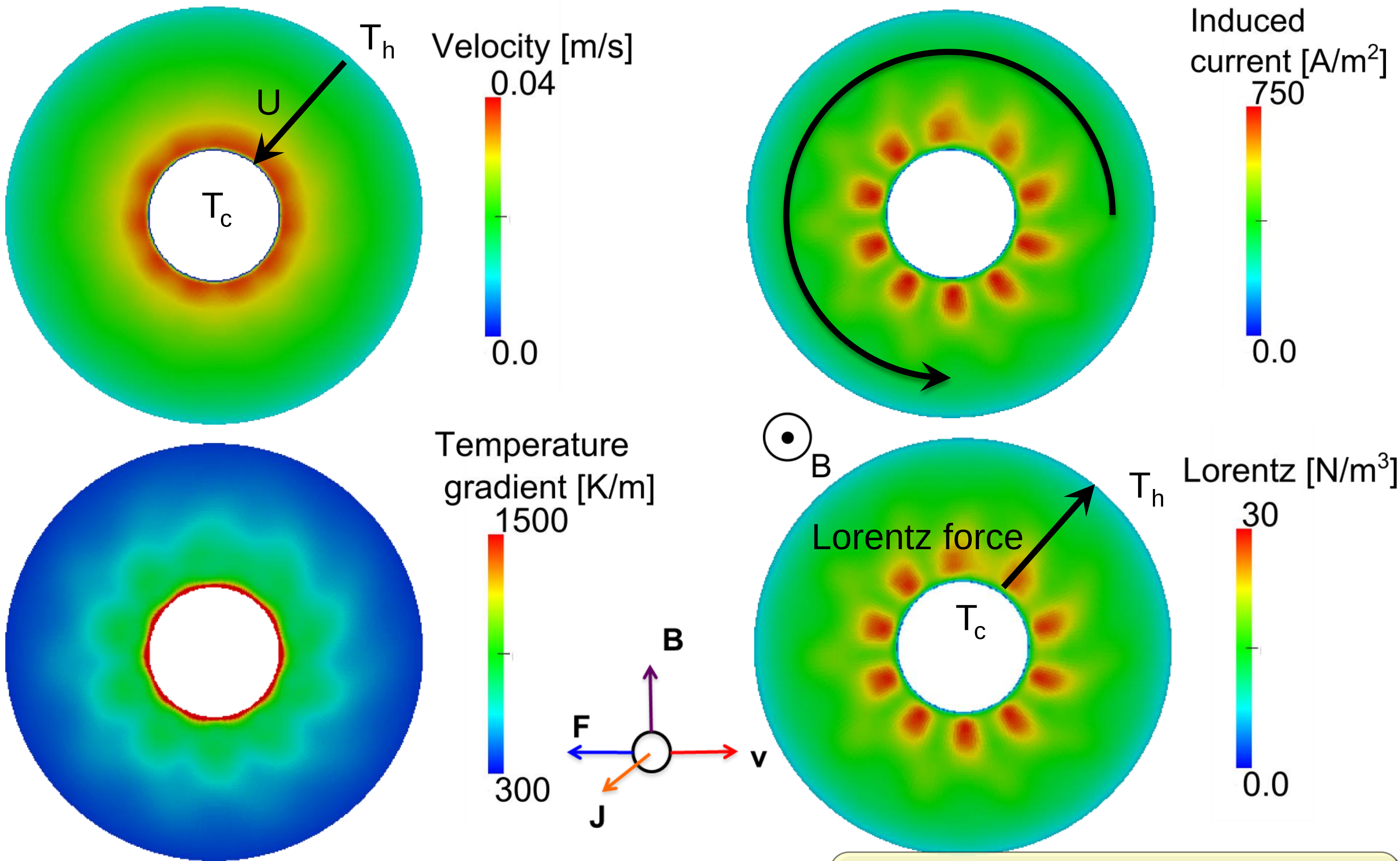


Time development of surface temperature at r = 20 mm.

Unsteady flow

Difficult to observation by crucible rotation

Effect of magnetic fields

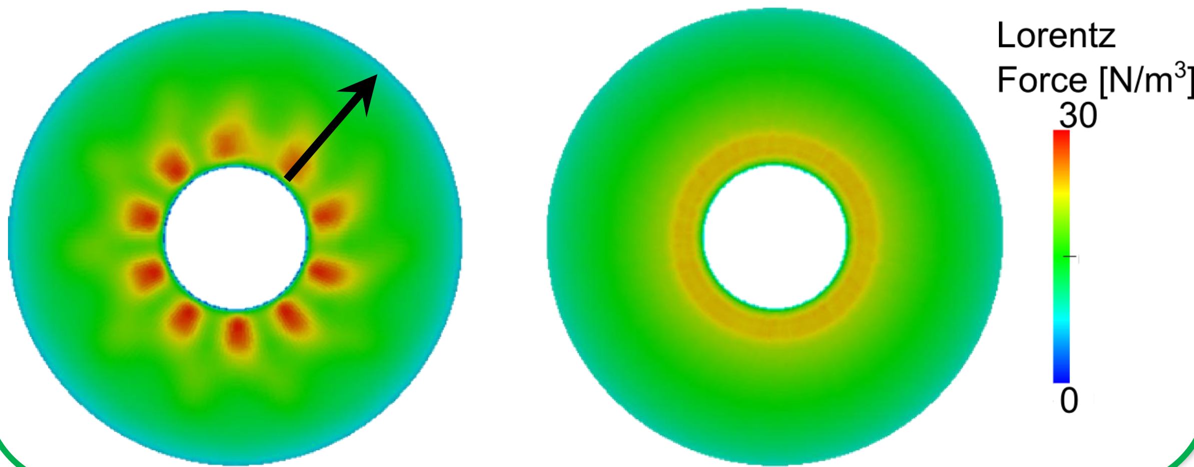


Marangoni effect $\mu \frac{\partial \mathbf{v}}{\partial \mathbf{n}} = \sigma_T \nabla T$

Lorentz force appeared at inner area on the surface.

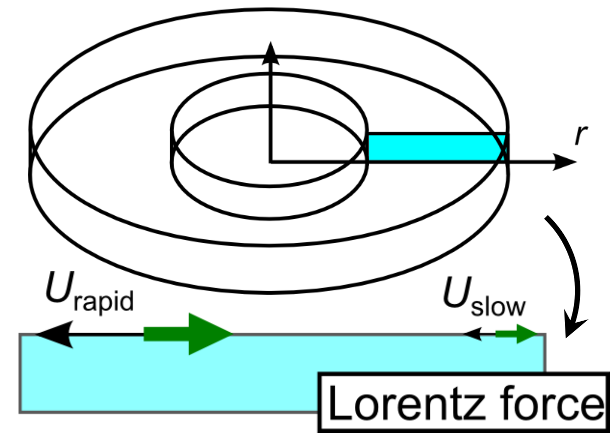
Alternative effect of crucible rotation and magnetic field

Lorentz force



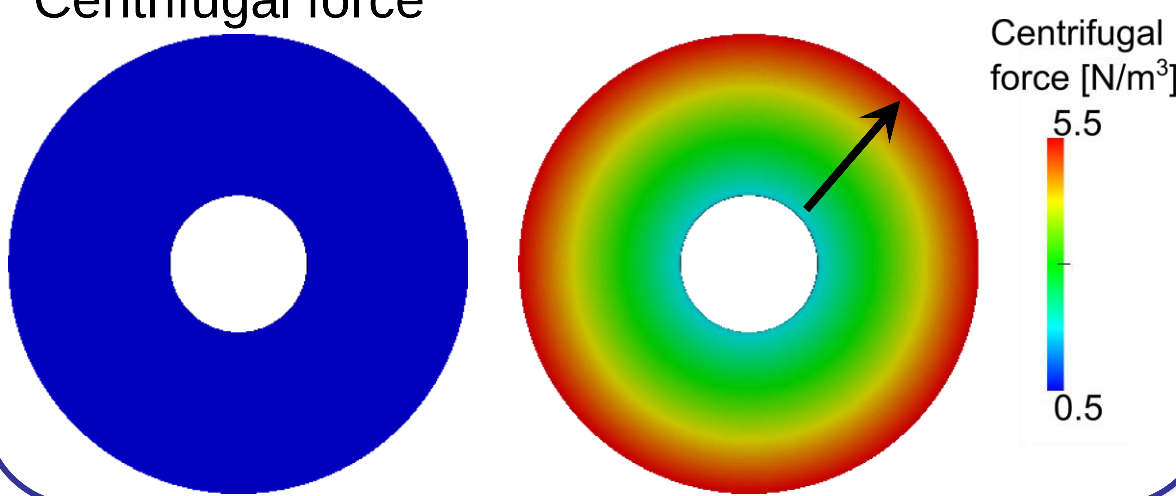
Ha = 7.5 and ω = 0 s^{-1}

Ha = 7.5 and ω = 2/60 s^{-1}

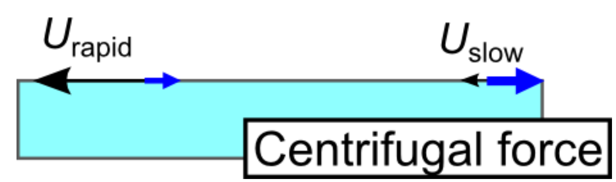


Lorentz force appears on the inner side.

Centrifugal force



$$\mathbf{F}' = \rho \mathbf{r} \boldsymbol{\omega}^2 \ [\mathrm{N/m^3}]$$



Centrifugal force appears on the outer side.

Conclusion

Magnetic field

- Magnetic field causes Lorentz force on the inner side.
  - More effective than crucible rotation only
  - Depends on Marangoni effect

Crucible rotation

- Crucible rotation causes centrifugal force on the outer side.
  - Difficult to control HTW because of weak force on the inner side

Effective control is available on HTW

by applying crucible rotation and magnetic field

Objective

Understanding of alternative effect of *Crucible rotation* and *Magnetic field* on HTW