Visualization of vapor film collapse mode during unsteady boiling on oil quenching by using cellular automaton simulation

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Agenda

✓Background

✓What is Cellular Automaton Simulation

✓Formulation of Quenching Phenomena by using Cellular Automaton

✓Correlation

- Cylinder Shape
- Cylinder Shape with Asymmetrical Boundary
- Bar shape with Keyway

✓Conclusion

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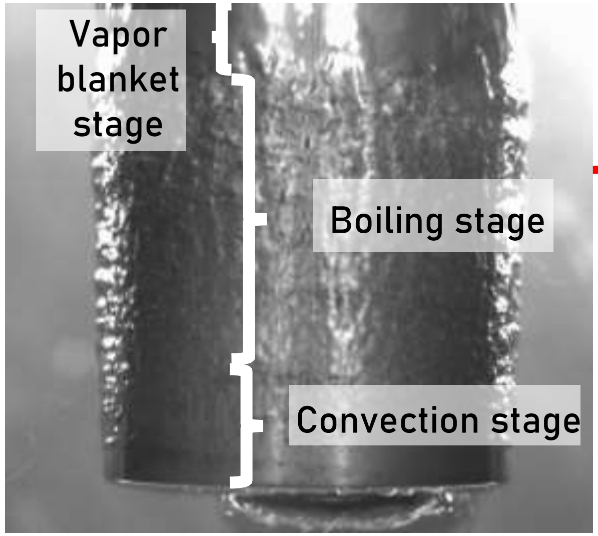
Background

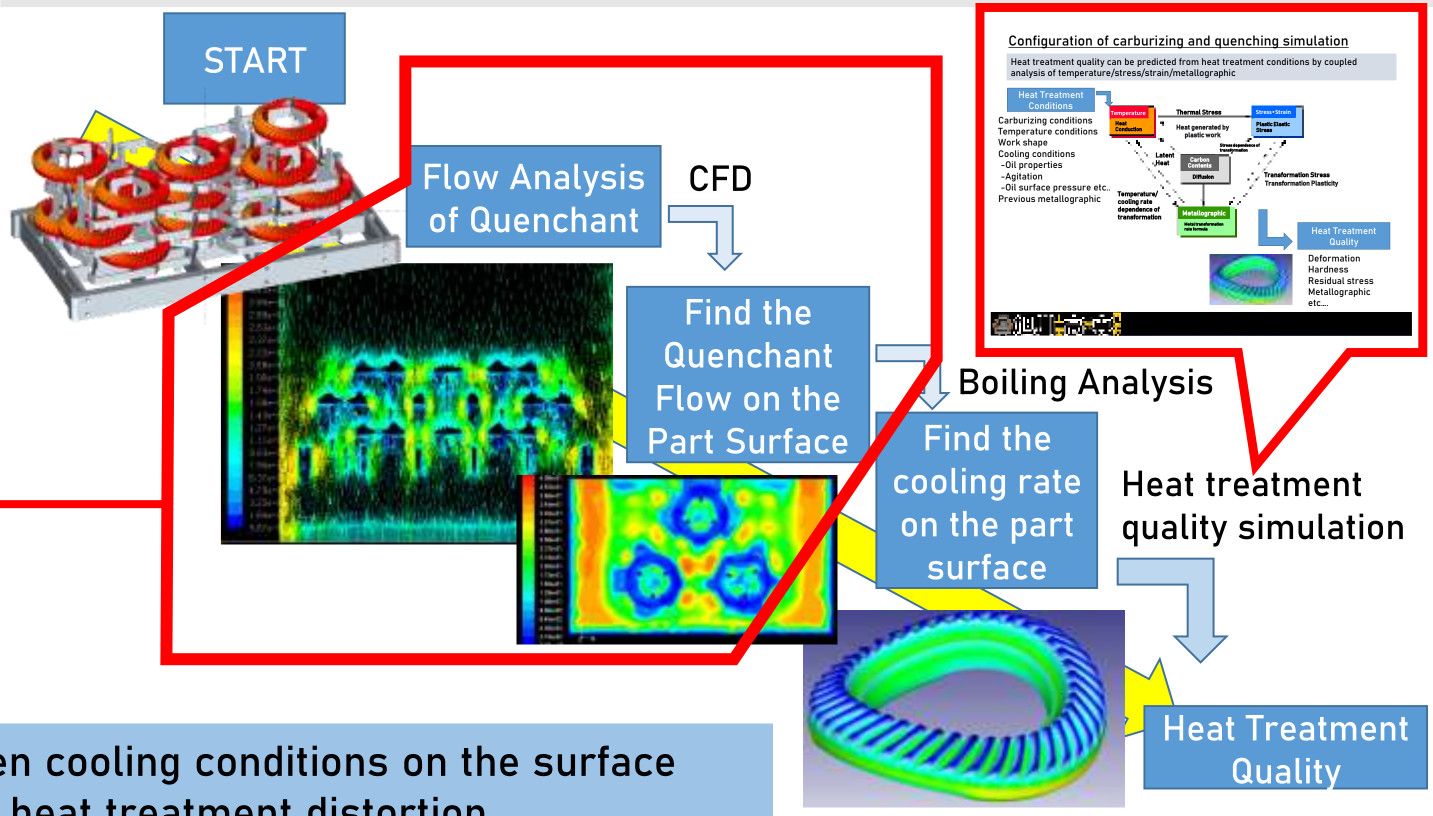
In heat treatment simulation of oil quenching process, it is necessary to solve the vapor blanket collapse mode and add boundary conditions to the part model surface.

Narazaki, M, Kogawara, M., Shirayori, A., Fuchizawa, S., Effect of Heat Transfer Coefficients on Simulation Accuracy of Quenching of Steel, *Journal of the Visualization Society of Japan*, 23(2), 197-200, 2003

Need Expensive calculation cost
Difficulties in complex shape



Configuration of Heat Treatment Simulation -Overall Flow-



Uneven cooling conditions on the surface affect heat treatment distortion

Influence of thermal boundary conditions on the results of heat treatment simulation, Tsuyoshi Sugimoto, Dong Ying Ju, Materials Transactions 59(6) 950-956 2018

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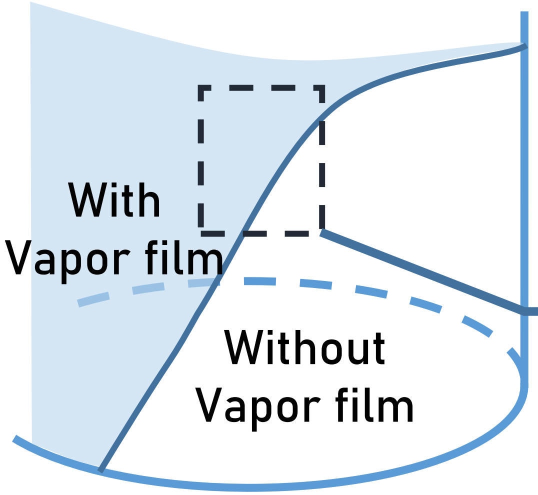
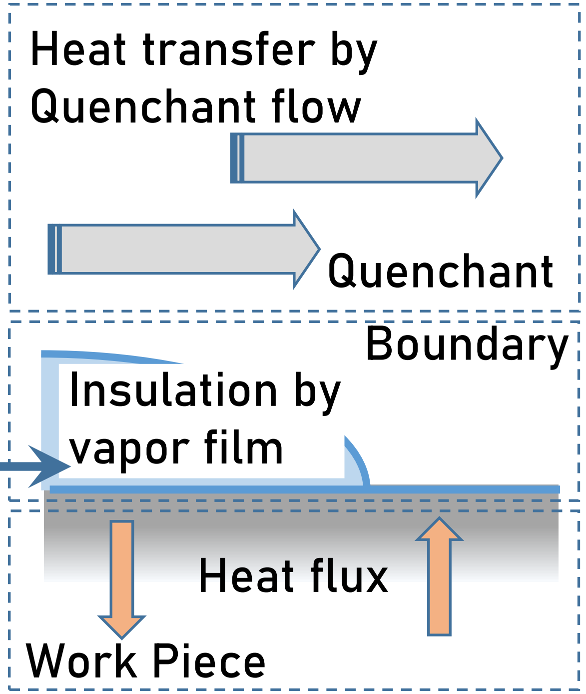
Scope of this research



Vapor film



Heat transfer phenomenon in quenching

	Time dependence	Dimension	Prior Situation
Quenchant flow	Flow component: Steady Heat transfer component: Unsteady	3	Strong Agitation Vapor Pool
Heat Transfer	Unsteady	2	Weak/Still Agitation Complex Shape
Heat conduction	Steady (Latent heat of transformation is unsteady)	3	Large Size

Calculation method between heat treatment simulation and computer fluid dynamics, Tsuyoshi Sugimoto, Kouichi Taniguchi, Shigenori Yamada, Toshiyuki Matsuno, Masaru Sonobe, Dong Ying Ju, Materials Performance and Characterization, 2018, 8(2) 37-49

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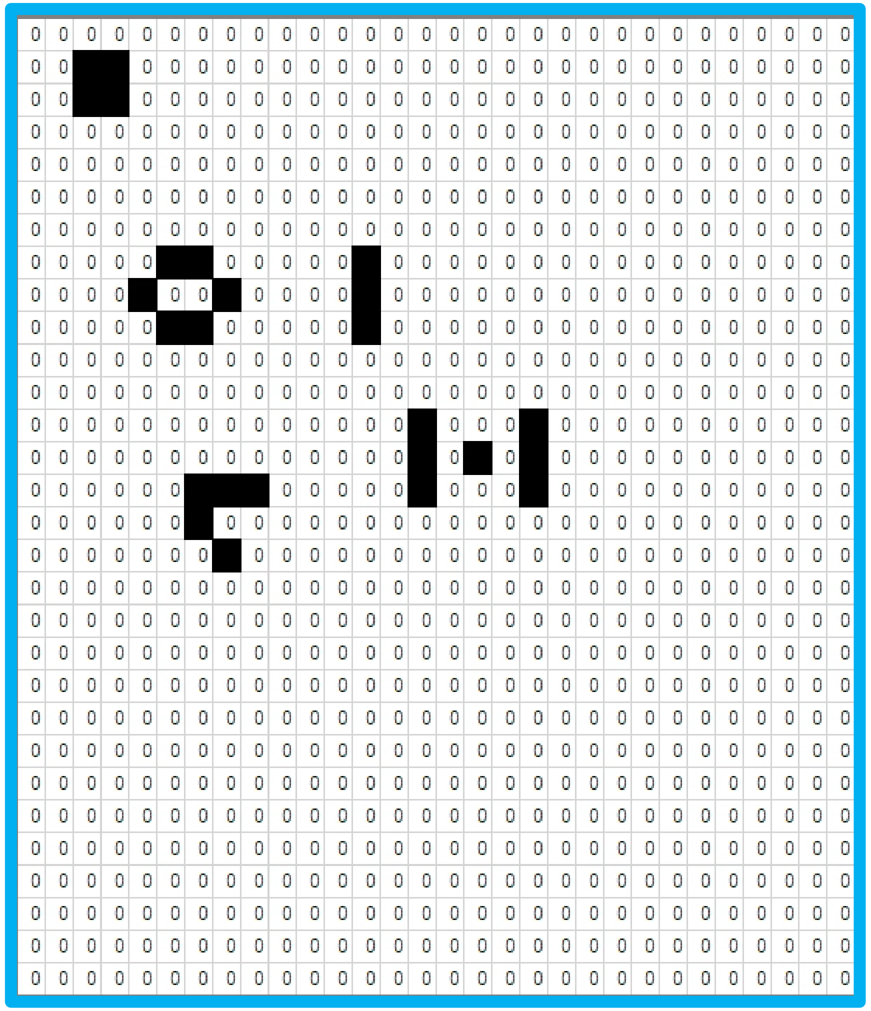
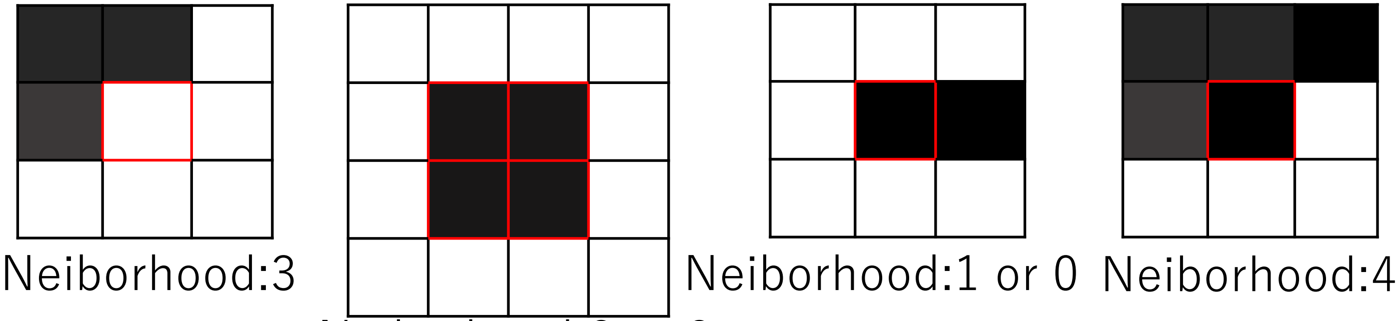
What is Cellular Automaton?



Typical Cell Automaton(LIFE GAME)

Rule of LIFE GAME



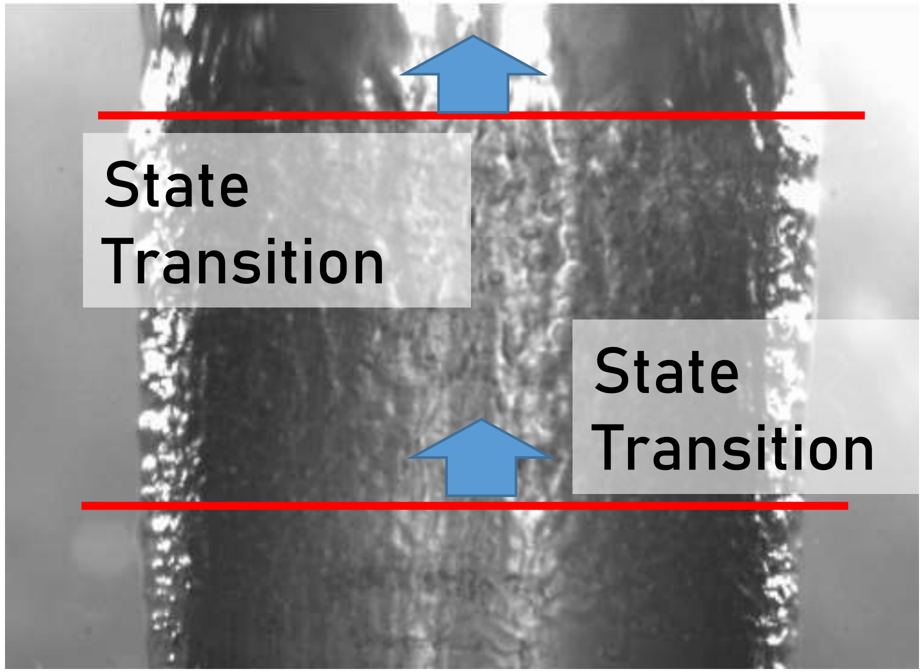
BIRTH	LIFE (Suitable Density)	DEAD (Depopulation)	DEAD (Overcrowding)

Interesting cell　LIFE　DEAD

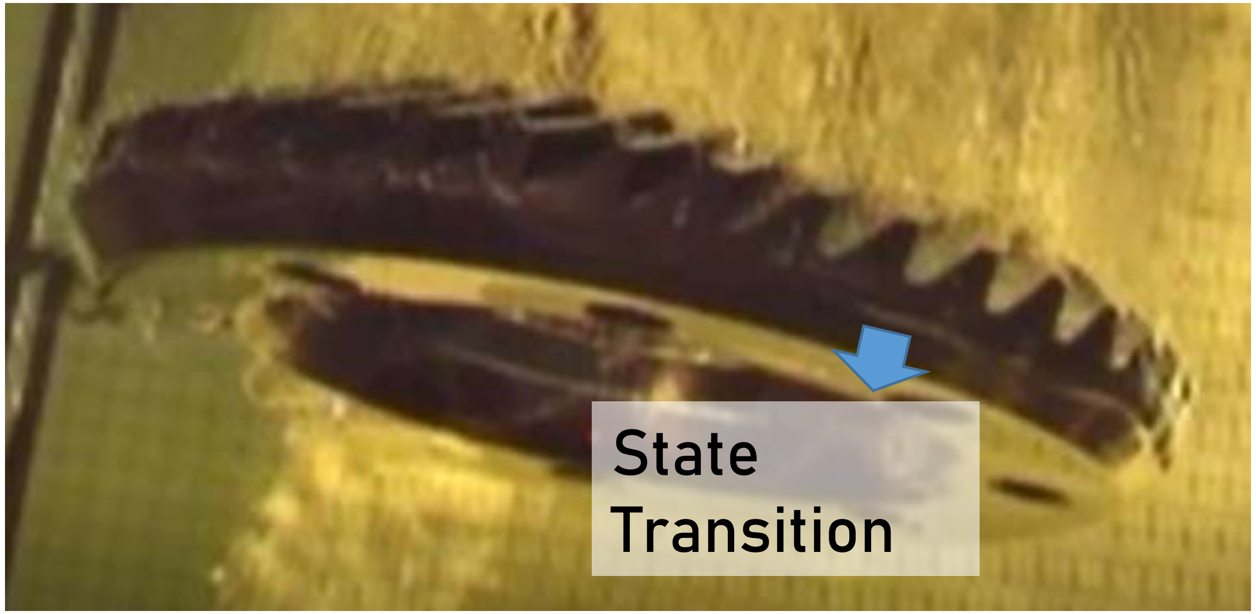
- ✓ Calculation method for **state transitions** (time evolution) devised by Von Neumann, the father of computers, in 1940
- ✓ Calculation speed is very fast because it is always **Turing-complete** (does not diverge)

Confirming the Boiling Phenomenon in Quenching

The boiling phenomenon in quenching is a two-dimensional one on part surface
->State transition can be estimated by a cellular automaton.



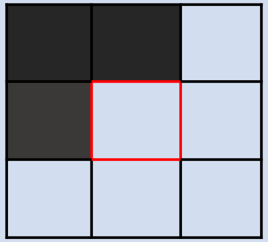
Quenching in Cylinder



Quenching in Hypoid Gear

Advantage of Cellular Automaton Method

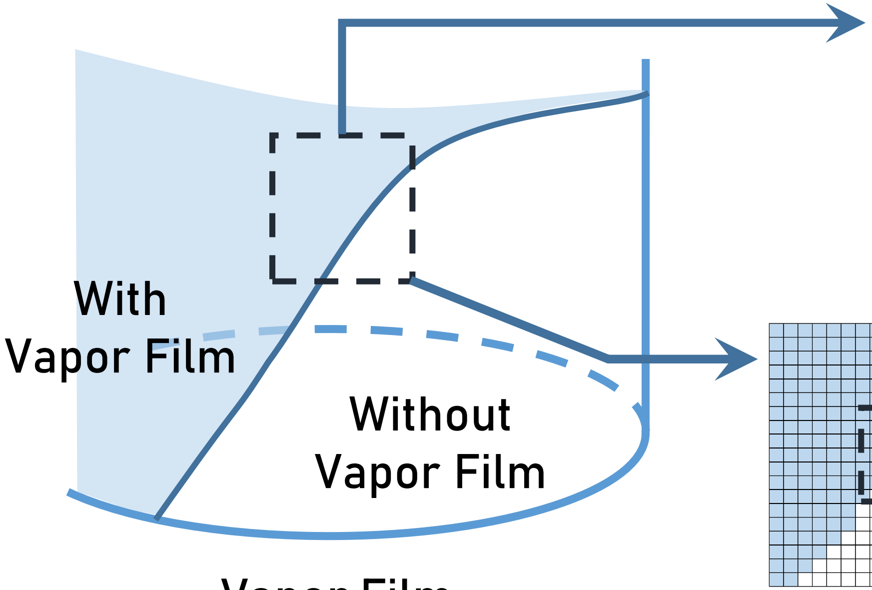
Compared to FEM/FDM (standard fluid analysis method), cellular automaton method are suitable for simple shape and complex boundary condition calculations.

	Cellular Automaton	FEM/FDM
		 Computational fluid dynamic (CFD) image of the Hyper - X at the Mach 7 test condition with the engine operating, NASA
Element Number	Low	High
Convergence(Calculation Cost)	Complete	In-complete
Complex Boundary Conditions	Easy	Possible
Multi Phase	Easy	Possible
Moving Part	Difficult	Easy
High Dimension	Difficult	Easy

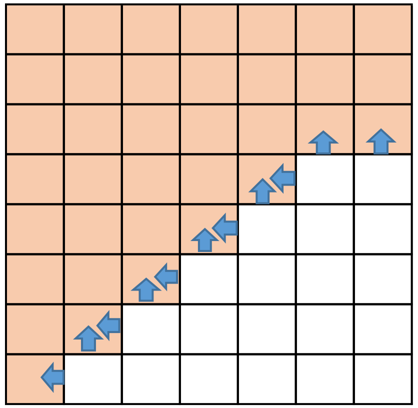
Advantage point

Application of Cellular Automaton to Boiling Phenomena

Purpose：In this research, we realize an ultra-low-cost oil quenching simulation by a low-dimensional (2-dimensional) cellular automaton.

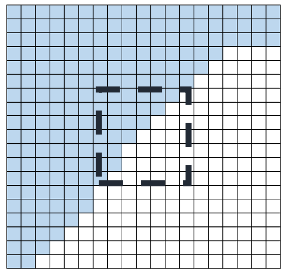


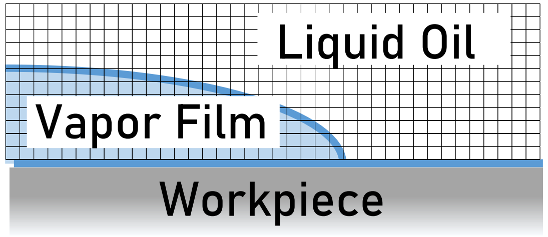
<u>Vapor Film</u>



Perspective of Calculation:
phase transition and Propagation

<u>This research：Low dimentional cellular automaton</u>





Perspective of Calculation:
the Status of Each Grid Point

<u>Conventional：3-dimentional CFD</u>

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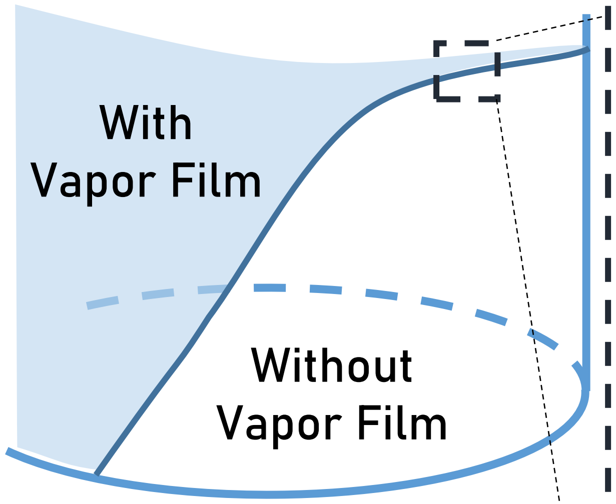
Basic Formulation



Vapor Film

Perspective Cell

	S_4^t	
S_2^t	S_0^t	S_1^t
	S_3^t	

Phase Change:
Von Neumann Neighborhood
(Weakly affected by surroundings cells)

T_8^t	T_4^t	T_5^t
T_2^t	T_0^t	T_1^t
T_3^t	T_3^t	T_7^t

Temperature:
Moore Neighborhood
(Strongly affected by surroundings cells)

S_i^t : Phase
0: Vapor Blanket Stage
1: Boiling Stage
2: Convection Stage

t:time
i:Position

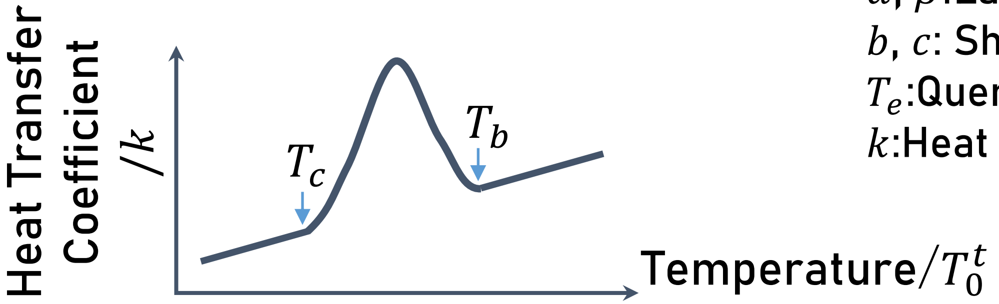
T_i^t : Temperature

Wolfram, S., *A New Kind of Science*, Wolfram Store, 2007

Phase Change : $S_0^t = 0$ and $\sum_i S_i^t \geq b$ and $T_0^t \leq T_b$ then $S_0^{t+1} = 1,\ T_0^{t+1} = T_0^t - \alpha$ ··Eq. (1)

$S_0^t = 1$ and $\sum_i S_i^t \geq c$ and $T_0^t \leq T_c$ then $S_0^{t+1} = 2,\ T_0^{t+1} = T_0^t - \beta$ ·· Eq.(2)

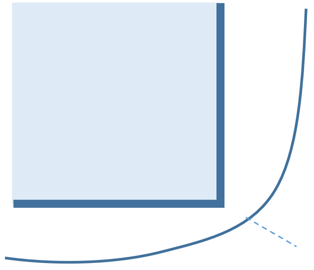
Temperature : $T_0^{t+1} = T_0^t + \left\{\frac{1}{6}\left(T_1^t + T_2^t + T_3^t + T_4^t\right) + \frac{1}{12}\left(T_5^t + T_6^t + T_7^t + T_8^t\right) - k \cdot \left(T_e - T_0^t\right)\right\}$ ·· Eq.(3)



α, β:Latent Heat
b, c: Shape Factor
T_e:Quenchant Temperature
k:Heat Transfer Coefficient

Added Formulation for Actual Process
Tilt, Edge Shape and Vibration(Fluctuation) of Vapor Film

Edge shape, tilt and Vapor film vibration, is reflected as vapor film thickness change on time evolution and position change.

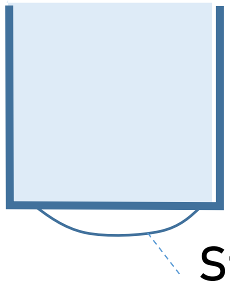


$b = b_0 - \delta$ ・・Eq. (5)

δ: Vapor film collapse due to edge

Thin Vapor film in Edge

Effect of Edge Shape



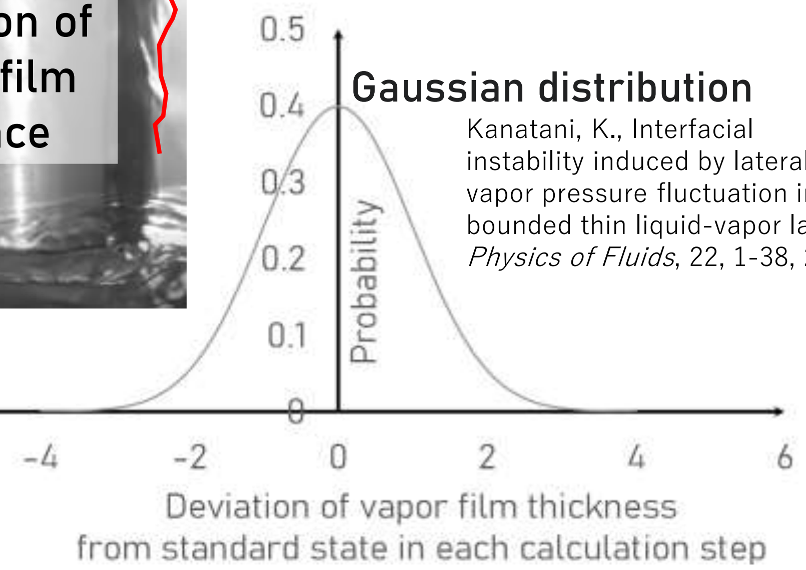
$b = b_0 - \varepsilon \cos\theta \,|\theta \leq 0$ ・・Eq. (6)

θ: Tilt of surface

(Horizontal:0, downward is minus)

Stayed Vapor film

Effect of Surface Tilt



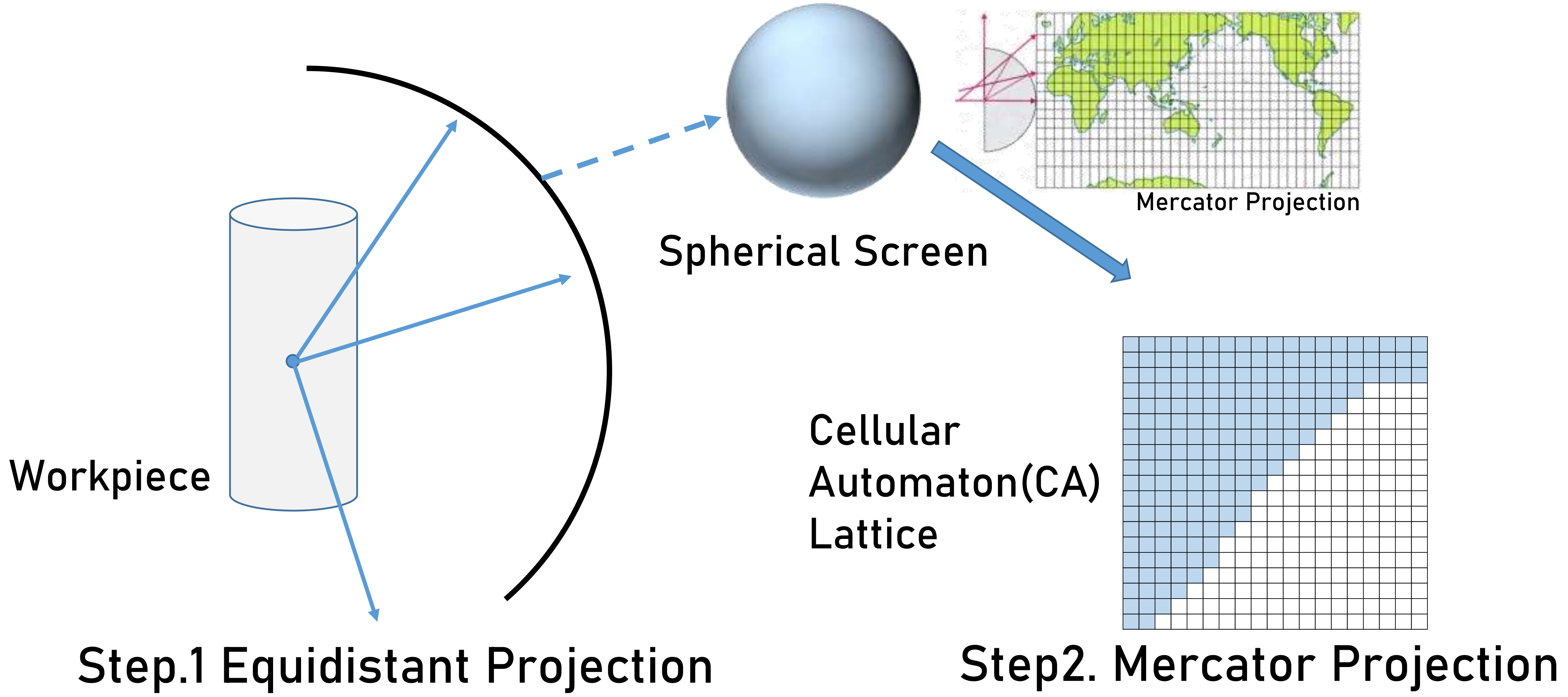
Kanatani, K., Interfacial instability induced by lateral vapor pressure fluctuation in bounded thin liquid-vapor layers, *Physics of Fluids*, 22, 1-38, 2009

$b = b_0 + \gamma N(\mu, \sigma^2)$ ・・Eq. (4)

γ, μ, σ: Control parameter for vapor film vibration

Effect of Vapor film vibration

Projecting Workpiece Shape onto CA Lattice



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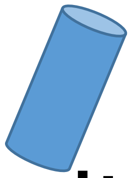
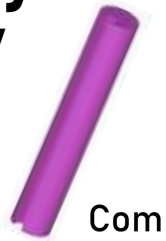


Reproduction of normal heat transfer

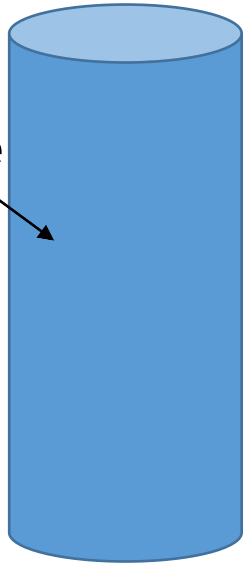
Asymmetrical Cooling



Complex shape

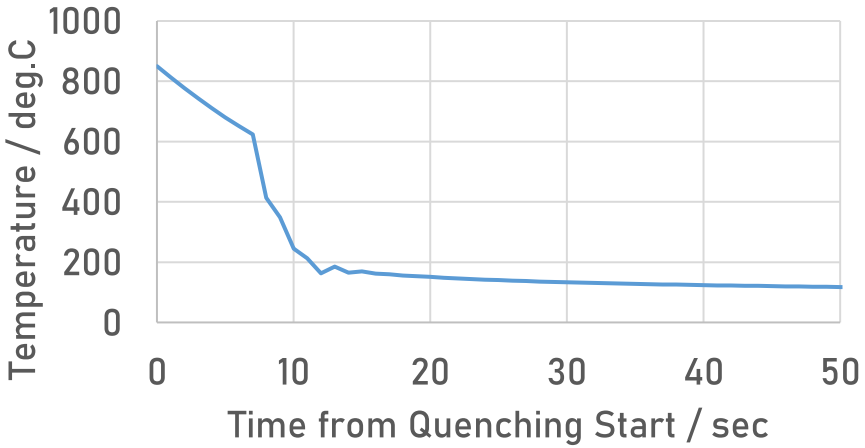
✓Conclusion

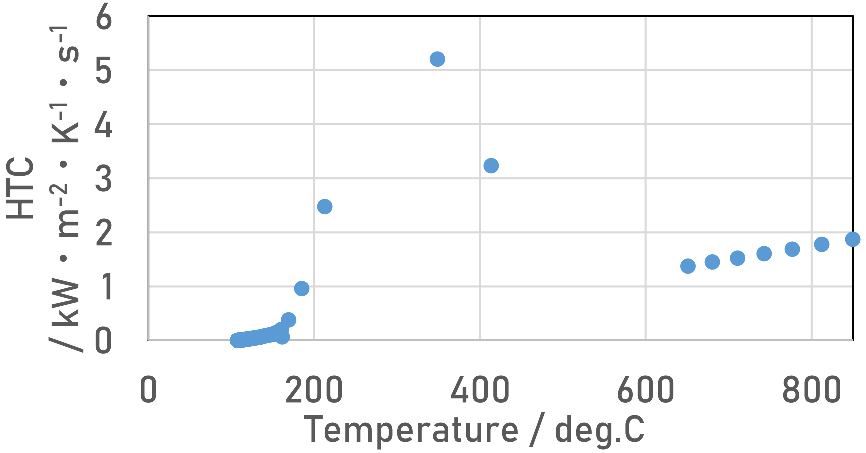
Correlation -Cylinder Shape-



Φ20mmx60mm
Cylinder

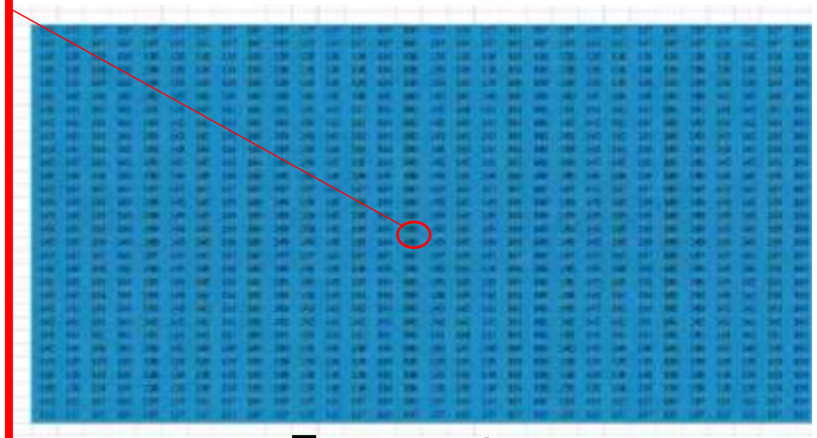
Quenchant:
Idemitsu High-Temp X
850deg.C->100deg.C





Temperature
(Full scale in same time)

Real-time simulation is possible by using cellular automaton method



Temperature
(Full scale in Full Time)

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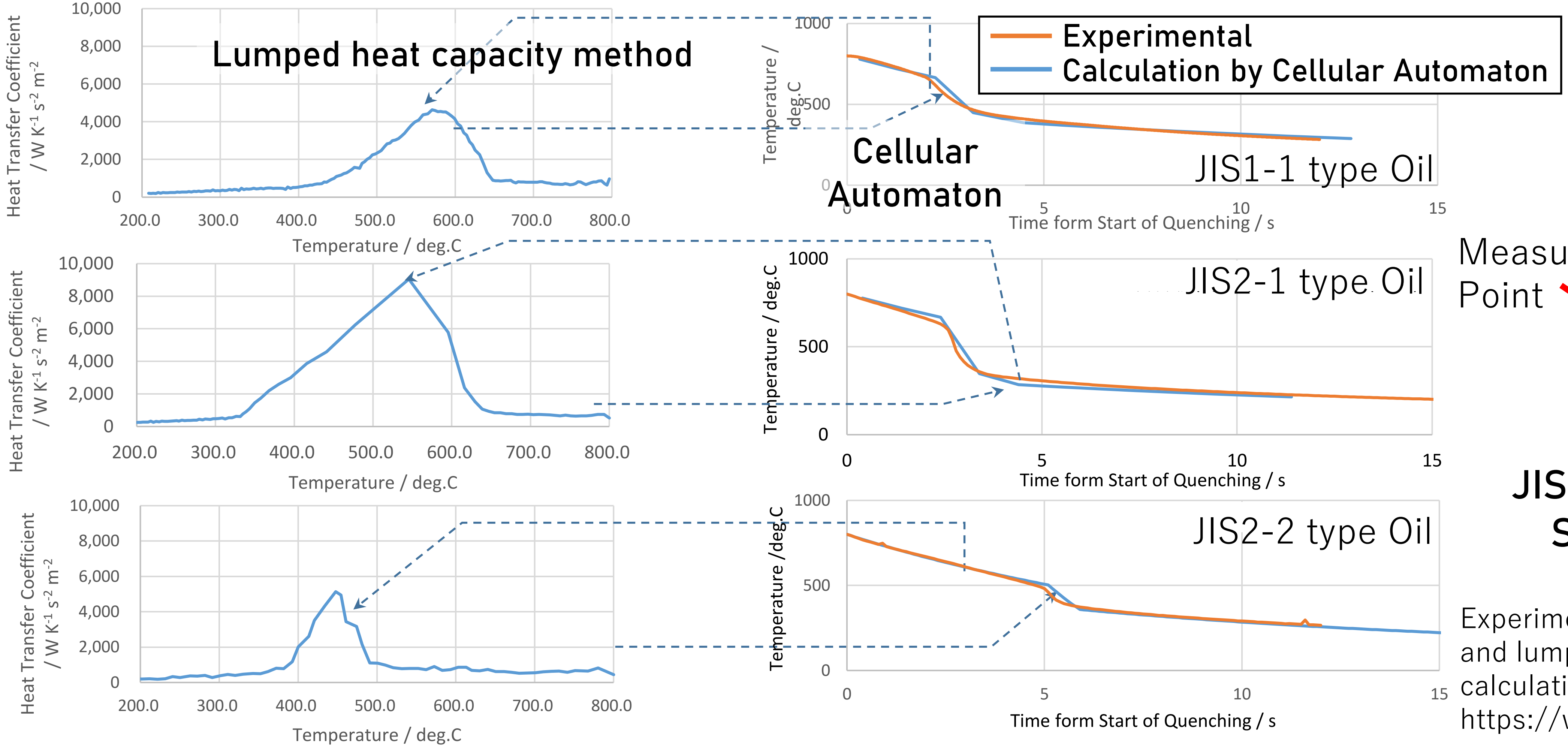
Correlation -Cylinder Shape-

Characteristics of oil and each cooling curve is be able to reproduce

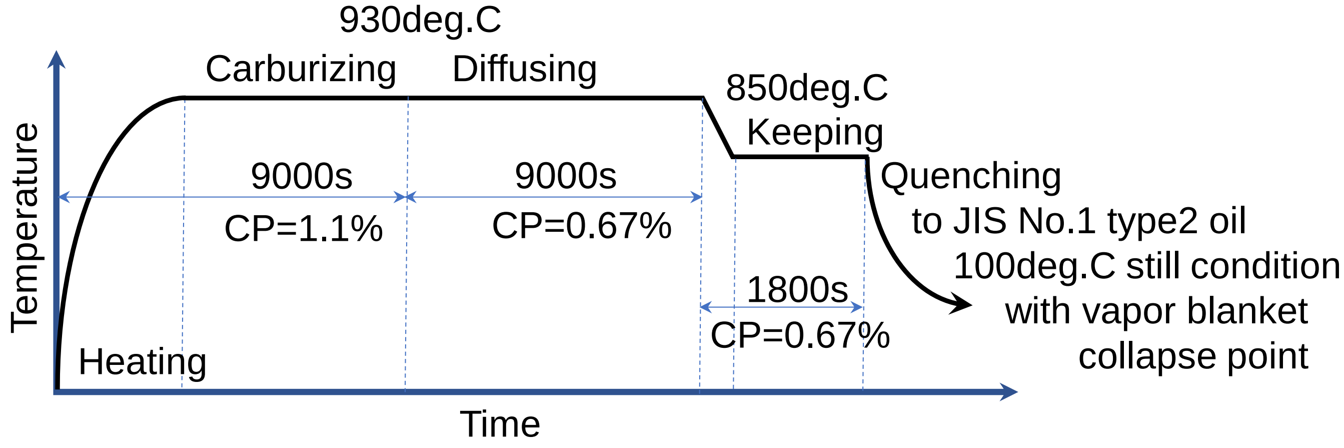


JIS K2422 type A Silver Probe

Experimental cooling curve and lumped heat capacity calculation: https://www.jsht.or.jp/study/

Correlation
-Cylinder Shape with Asymmetrical Boundary-

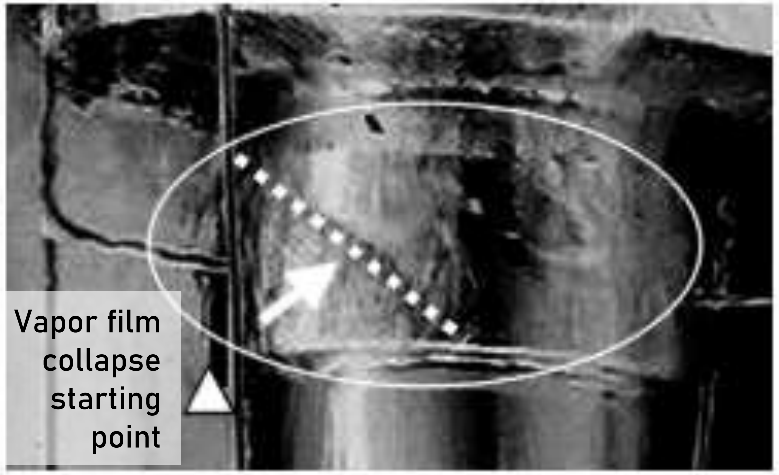
Heat Treatment Condition in This Simulation



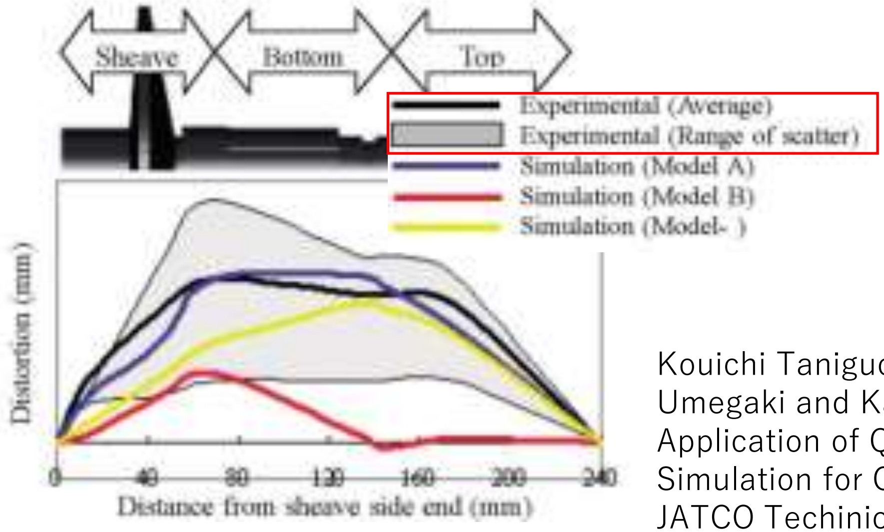
Simulation conditions

Solver	SFTC DEFORM-HT ver12.1
Element type	Hexagonal with coating mesh
Nodes	35,558
Elements	33,540

Example of Axial Bending in Pulley Quenching (Experiment)



Collapse mode of Vapor film

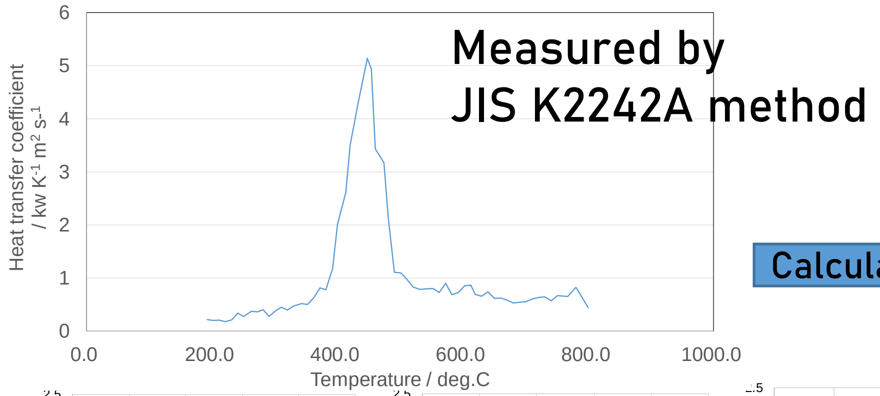


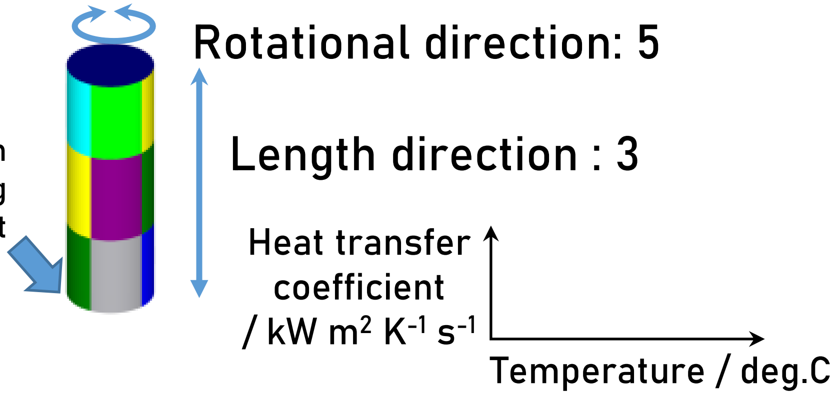
Result

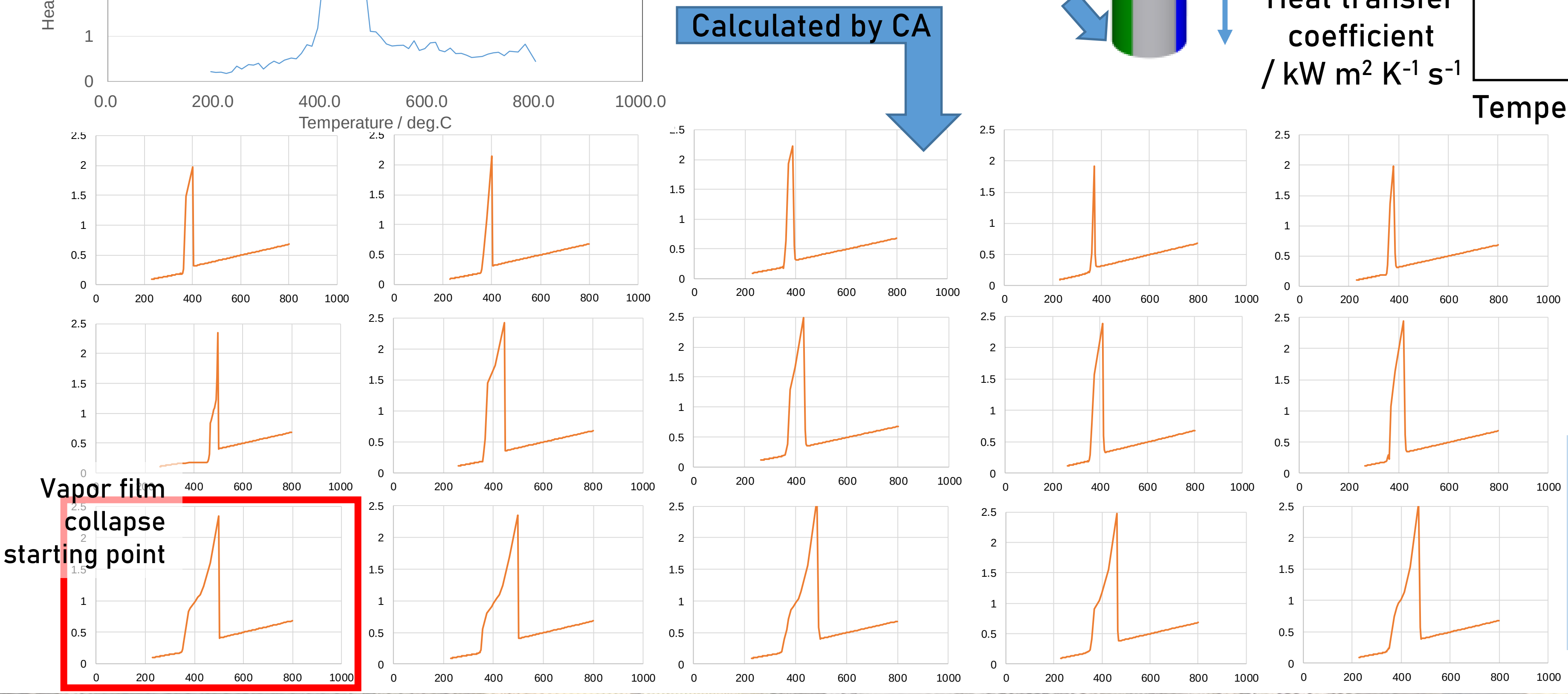
Kouichi Taniguch, Shunzou, Umegaki and Kanji Ueno, Application of Quenching Simulation for CVT Pulleys, JATCO Techinical Review No.7, pp. 88-94

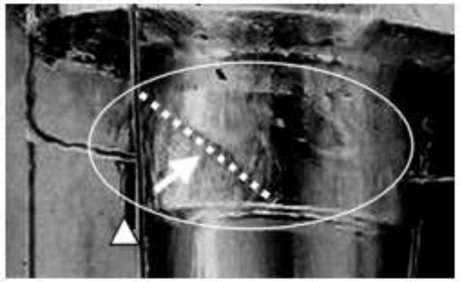
Correlation
-Cylinder Shape with Asymmetrical Boundary-

Estimation of Heat Transfer Coefficient Distribution on Cylinder Surface



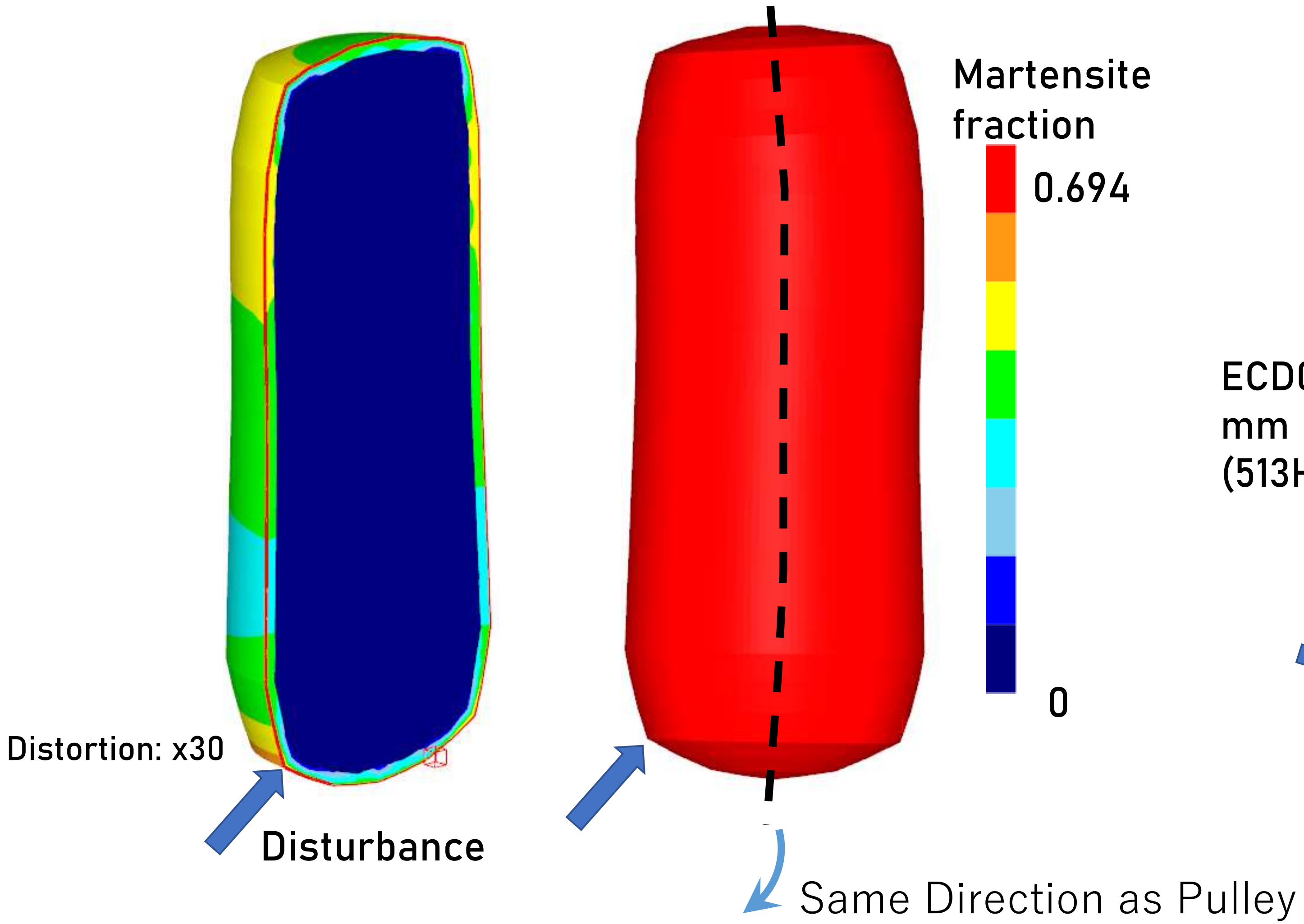


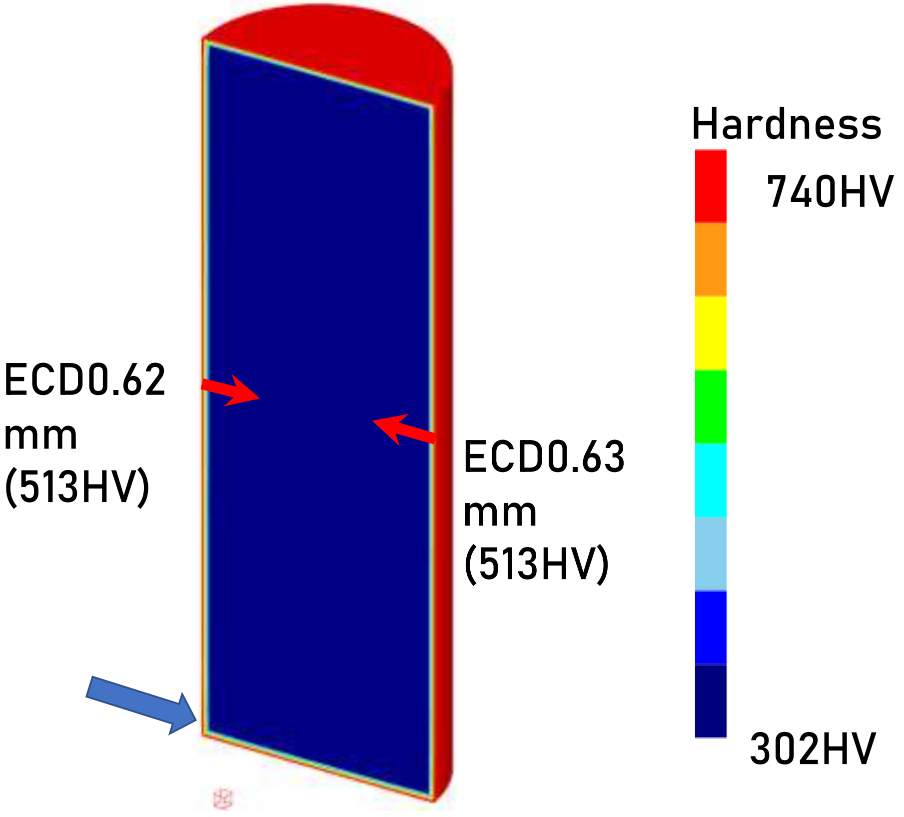




Heat Transfer coefficient distribution is like as vapor film collapse mode of CVT Pulley in past research.

Correlation
-Cylinder Shape with Asymmetrical Boundary-

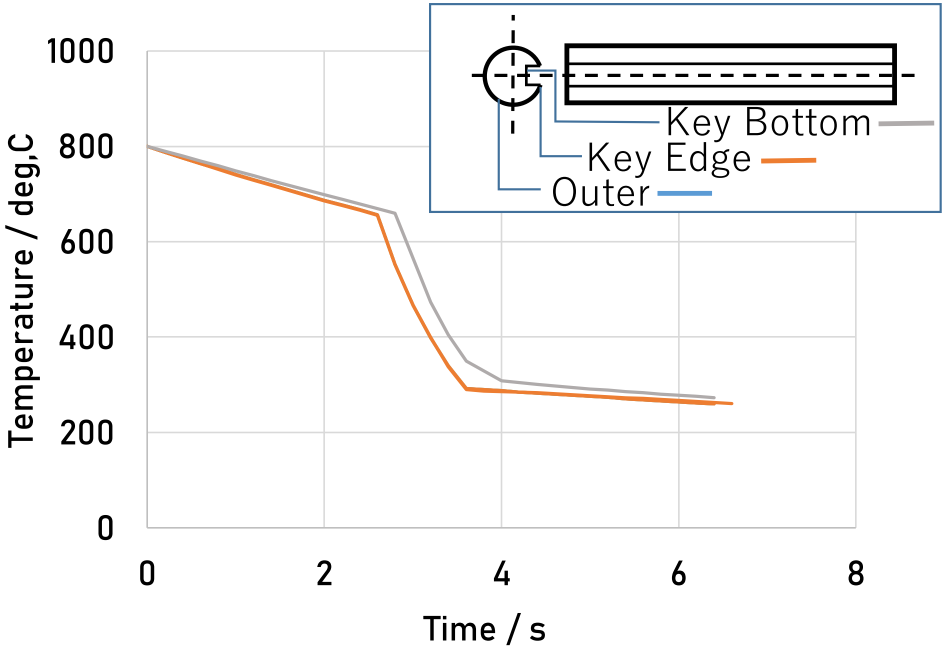


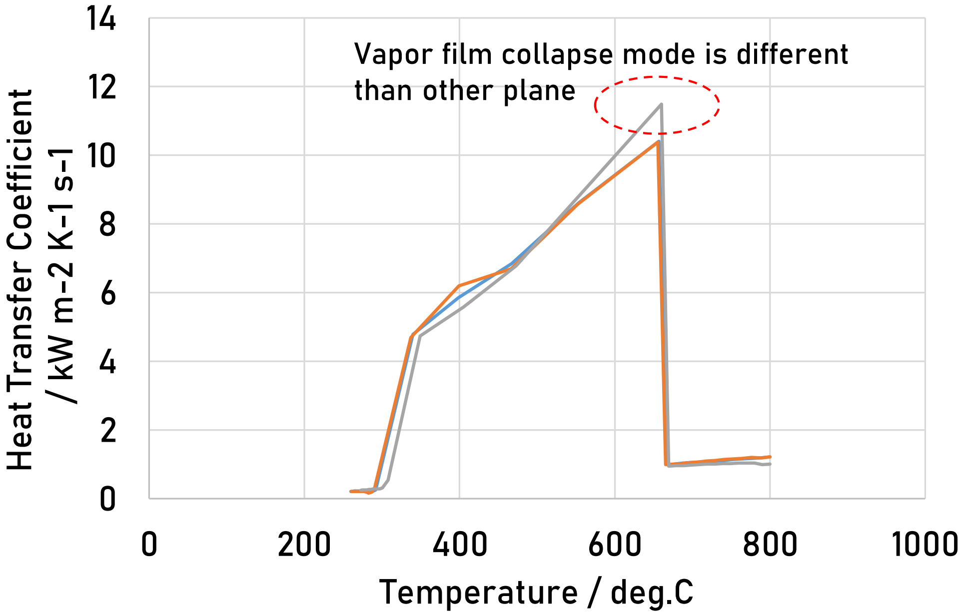


Bending direction is same as Experiment on Pulley

Correlation –Bar shape with Keyway-

- The cooling speed is effected with edge sharpness.
- In the Key bottom plane, cooling speed is rapid than other position, because of the propagation of collapse of boiling film from key edge.

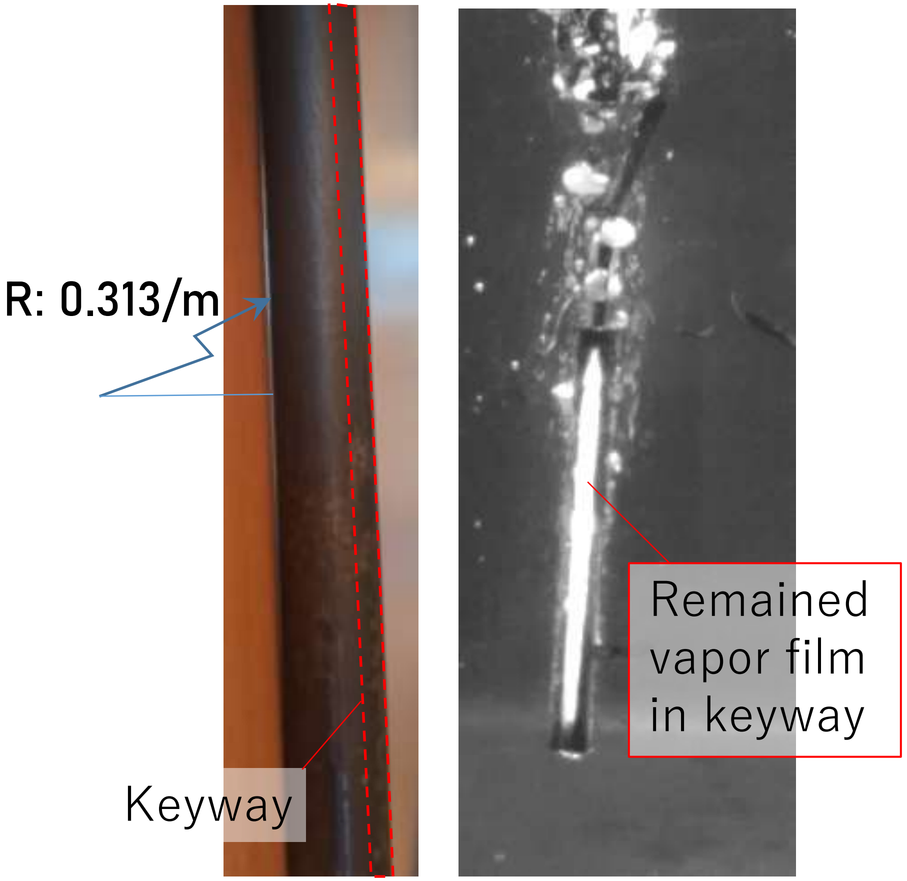




60mm

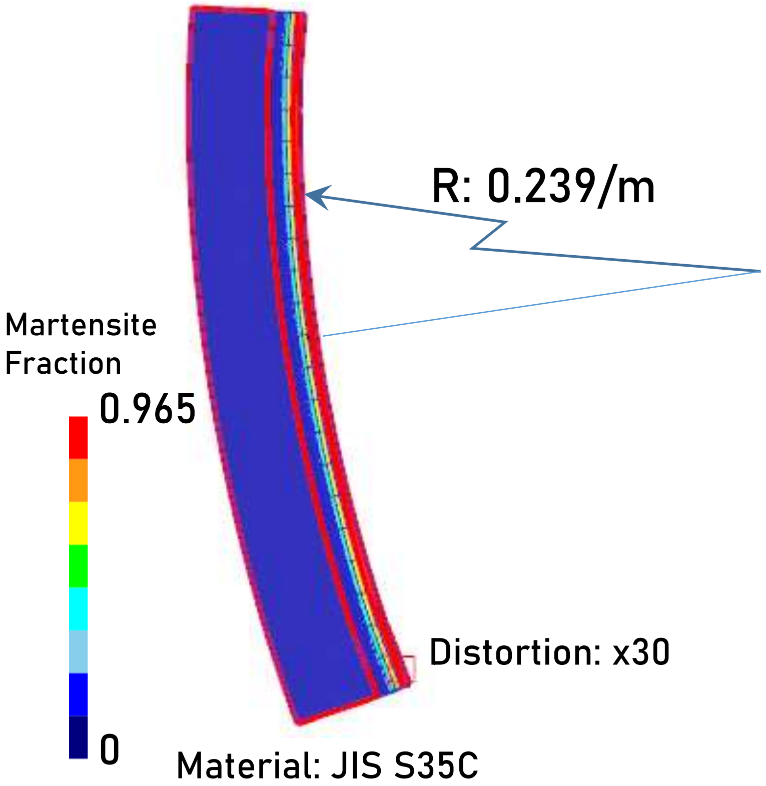
Quenchant: JIS2-1 type Oil

Correlation –Bar shape with Keyway-



Experiment

SHODENSHA Speed Viewer
500fps, full aperture, normally open



Material: JIS S35C
Quenching Temperature: 800deg.C

Simulation

(Cellular Automaton + DEFORM-HT)

Bending direction is different between experiment and simulation.

Remained vapor film occur very slow cooling in keyway.

Reproduce method for Vapor film pools is required

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Conclusion

- ✓ By using a cellular automaton simulation, we are able to reproduce the vapor film collapse, cooling, and heat transfer coefficient in real time speed

- ✓ With this method, characteristics of oil and each cooling curve is be able to reproduce .

- ✓ With this method, shape factors such as edges and corner R can be incorporated into the calculation.

- ✓ The reproduce method for Vapor film pools is required.

Next

- ✓ Reproduce complex quenchant flow(Vapor pool etc..), mass production settings

Acknowledges

This work was supported by JSPS KAKENHI Grant Number JP21K14061 “Quenching simulation including manufacturing variations by the low-dimensional cellular automaton method”

END