Modeling of Variation on Oil Quenching with Iterative Treatment Using Cellular Automaton

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Agenda

- ✓Background
- ✓Low dimension cellular automaton method
- ✓Simulation of heat treatment and cooling variations
- ✓Deformation analysis consider with heat treatment and cooling variations
- ✓Conclusion

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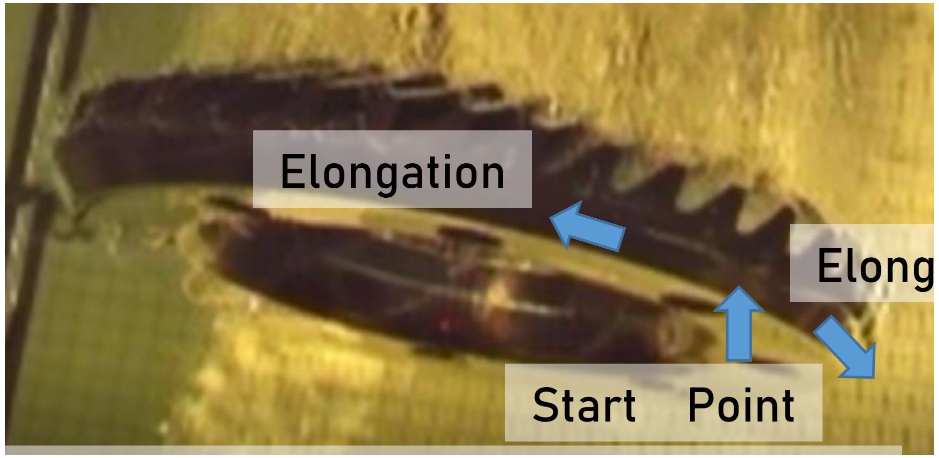
Relationship between Cooling state and Deformation

In heat treatment simulation of oil quenching process, it is necessary to solve the vapor blanket/boiling/convection each stage and add boundary conditions to the part model surface.

Require expensive calculation cost
Difficulties in complex shape

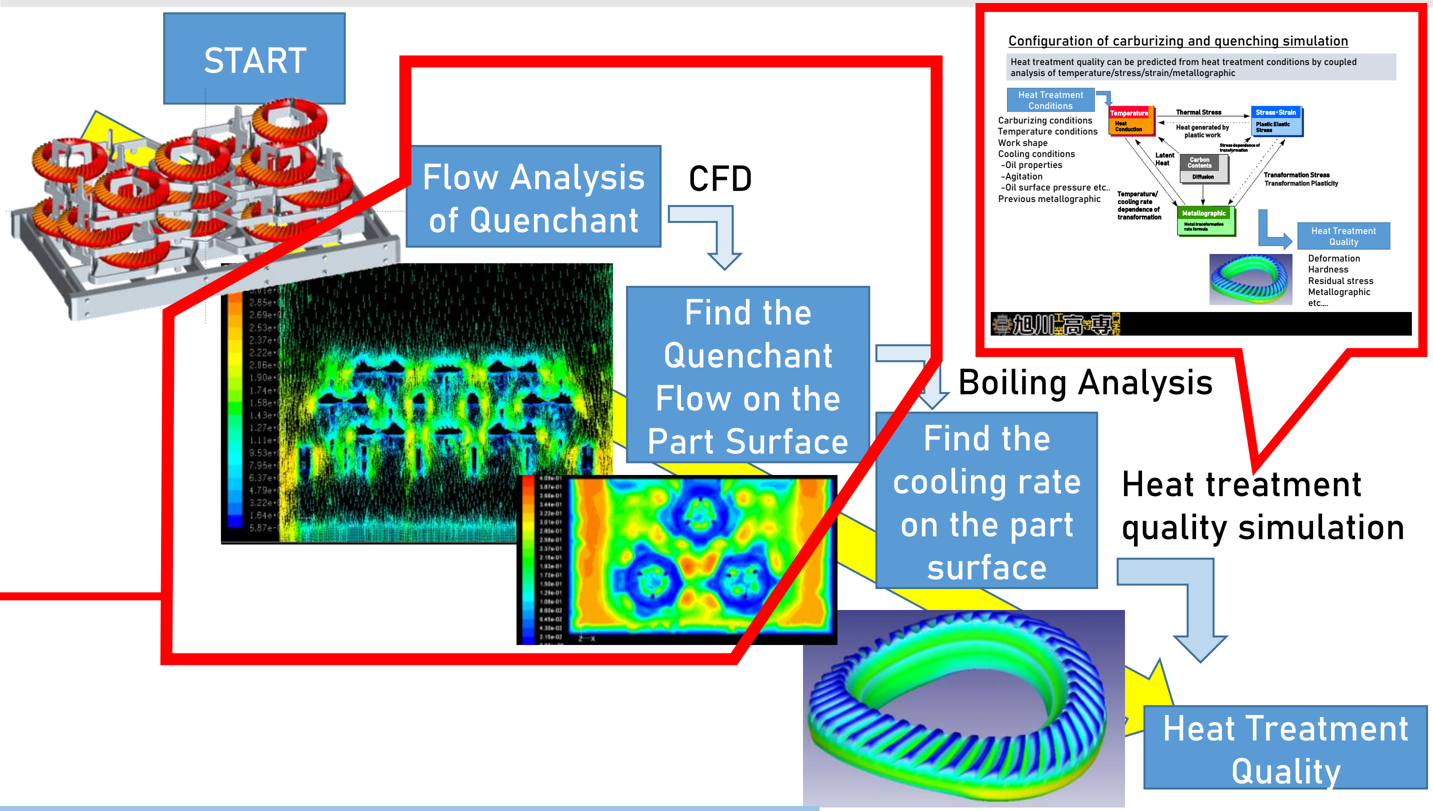
"Low dimensional cellular automaton"

Visualization of vapor film collapse mode during unsteady boiling on oil quenching by using cellular automaton simulation, Tsuyoshi Sugimoto, 27th International Federation for Heat Treatment and Surface Engineering, Saltzburg, Austria 2022



Schematic of Vapor Blanket Collapse

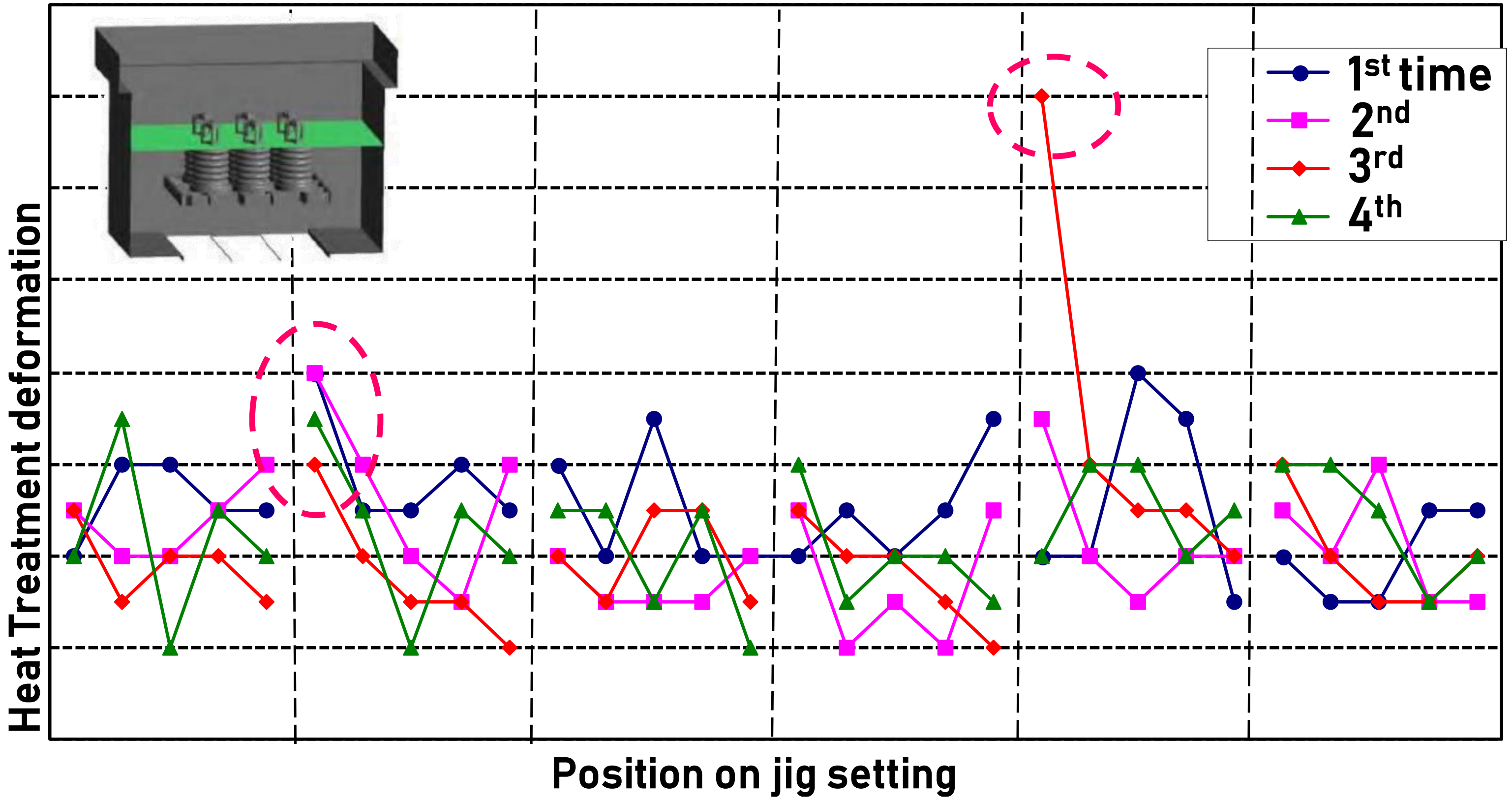
Configuration of Heat Treatment Simulation -Overall Flow-



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

Variation of Heat Treatment Deformation

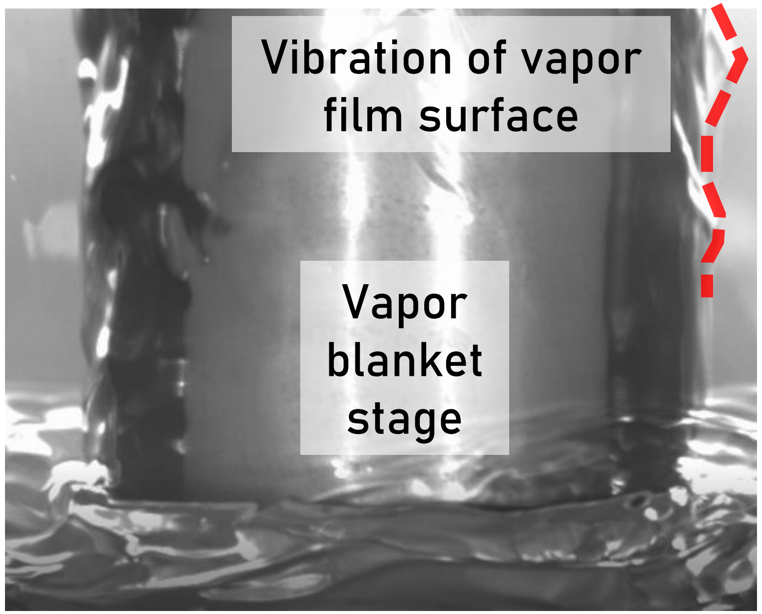


In mass production load setting and iterative quenching , at the specific position

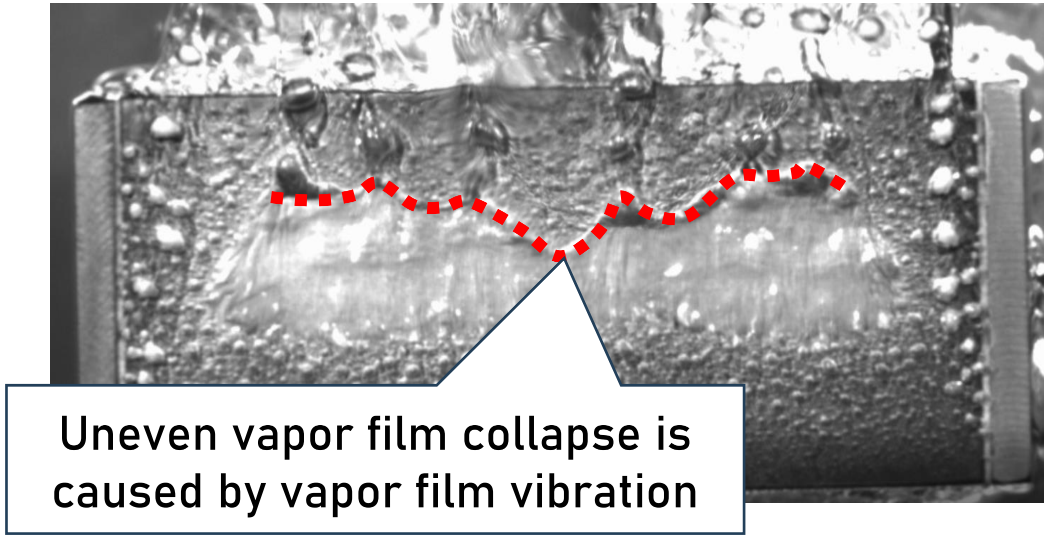
- ✓ The average value of quenching deformation may become large.
- ✓ Suddenly large heat treatment deformation appears due to repeated quenching processing ⇒"Deformation Variation"

The simulation method is required to reproduce repeated variations in oil quenching process.

Variation of Cooling



Vapor film vibration



Cooling variation

It is seemed that the variation in vapor film collapse is caused by the vibration of the vapor film.

This is one of the reason of variation of quenching deformation variation

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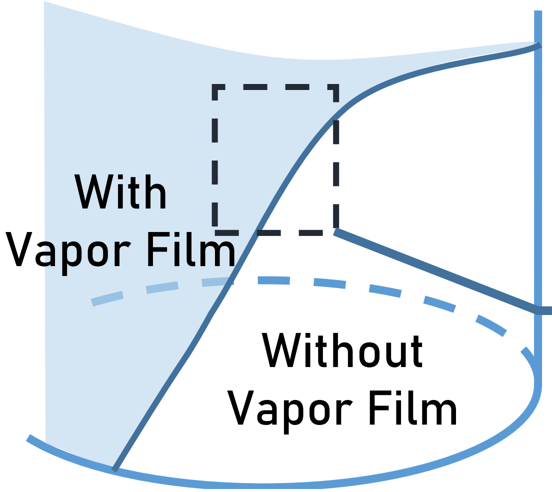
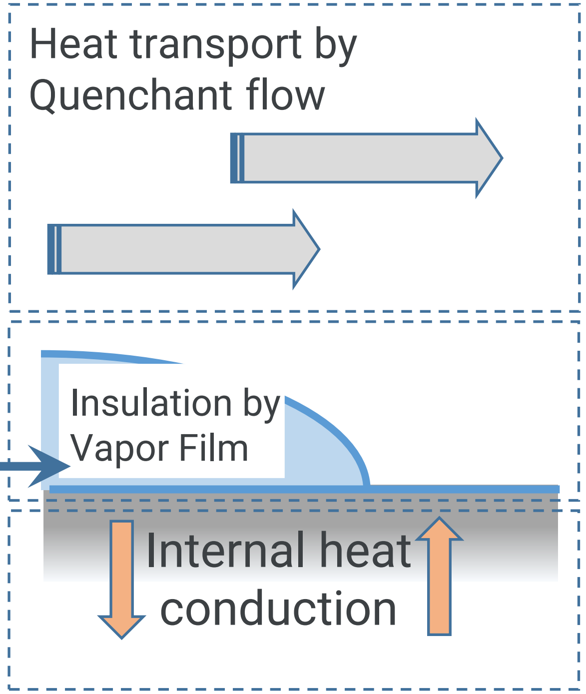
Low dimension cellular automaton



Vapor Film



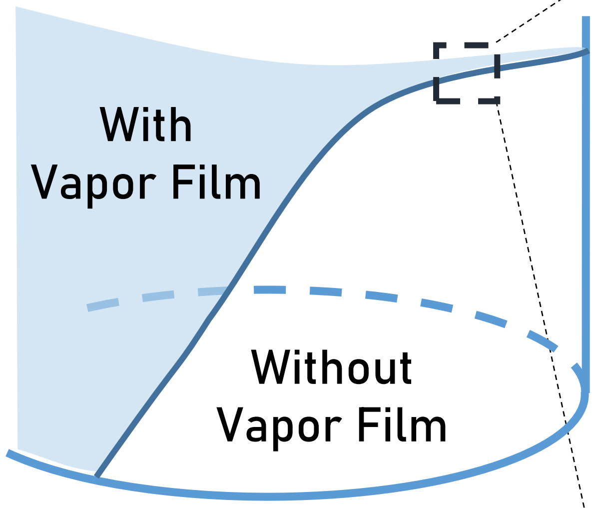
Phenomena

	time dependence	dimension	Prior Situation
Quenchant Flow	Flow component: Steady Heat transport: Unsteady	3	Strong Agitation
Heat Transfer	Unsteady	2	Weak/No Agitation Complex Shape
Heat Concuction	Steady (Latent heat is Unsteady)	3	Large Workpiece

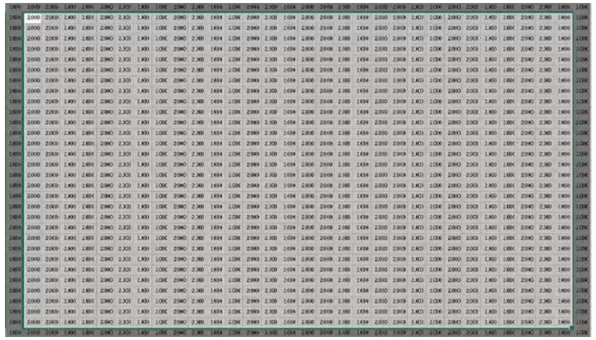
Calculation method between heat treatment simulation and computer fluid dynamics, Tsuyoshi Sugimoto, Kouichi Taniguchi, Shigenori Yamada, Toshiyuki Matsuno, Masaru Sonobe, Dong Ying Ju, Materials Performance and Characterization, 2018, 8(2) 37-49

Analysis of thermal insulation by vapor film allows prediction of specific cooling conditions with low load (two-dimensional)

Basic Equation



Vapor Film



Vapor film collapse using cellular automaton method

Phase transformation model by Wolfram

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

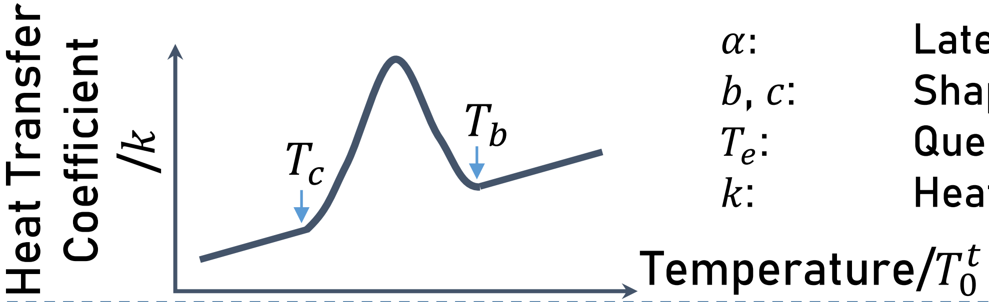
Sub-cool boiling model

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 $S_0^{t+1} = 2,\ T_0^{t+1} = T_0^t$ ・・Eq.(2)

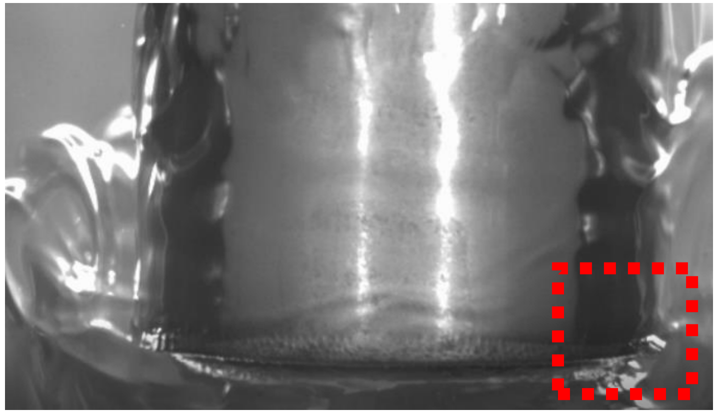
Temperature : $T_0^{t+1} = T_0^t + \left\{\frac{1}{6}\left(T_1^t + T_2^t + T_3^t + T_4^t\right) + \frac{1}{12}\left(T_5^t + T_6^t + T_7^t + T_8^t\right) - k \cdot \left(T_e - T_0^t\right)\right\}$ ・・Eq.(3)

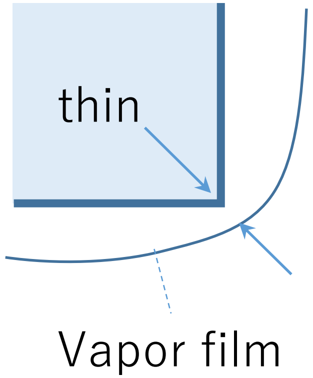


α: Latent Heat
b, c: Shape Factor
T_e: Quenchant Temperature
k: Heat Transfer Coefficient

Formulation of Sharp Edge Shape and Tilt of Vapor Film

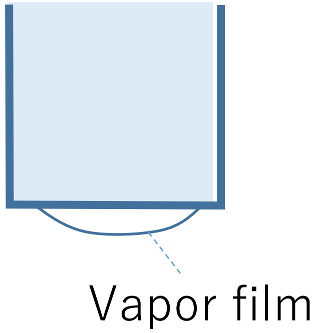
Sharp edge and tilt is reflected as position change of vapor film thickness.





$b = b_0 + \delta$ · · Eq. (5)

δ: decrease of vapor film thickness due to sharp edge



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

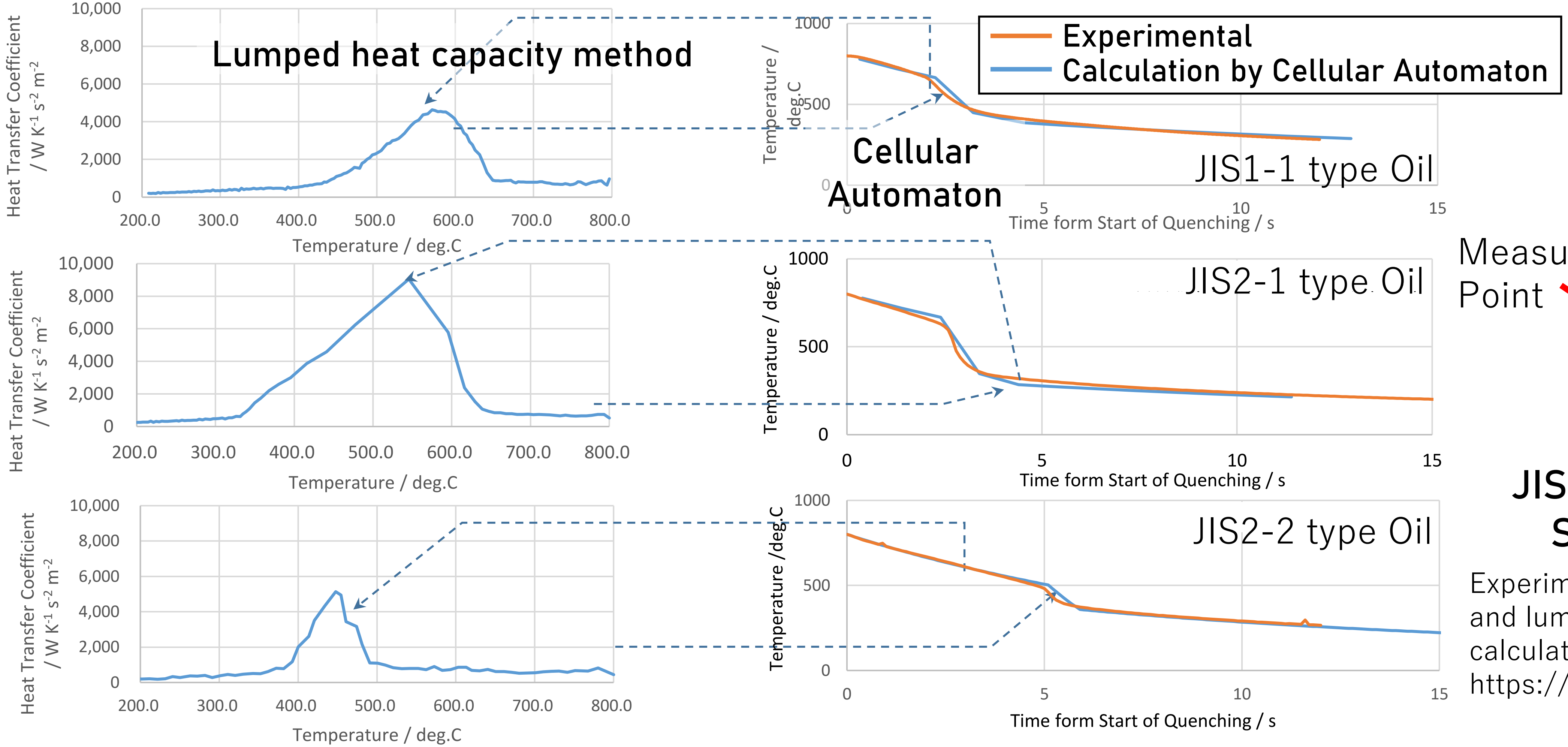
θ: Tilt of surface
(Horizontal:0, downward is minus)

Effect of Edge Shape

Effect of Surface Tilt

Verification by JIS silver bar prove

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/

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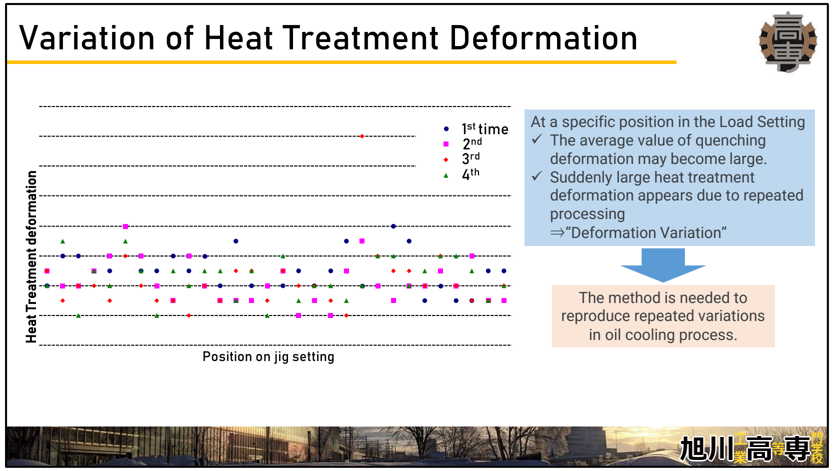
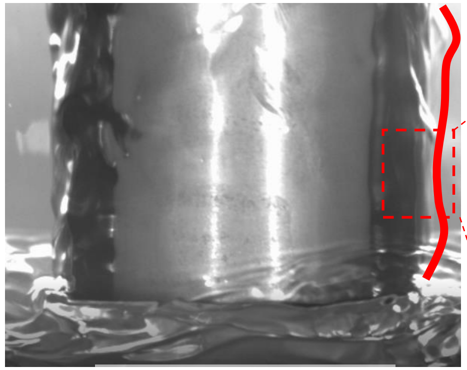
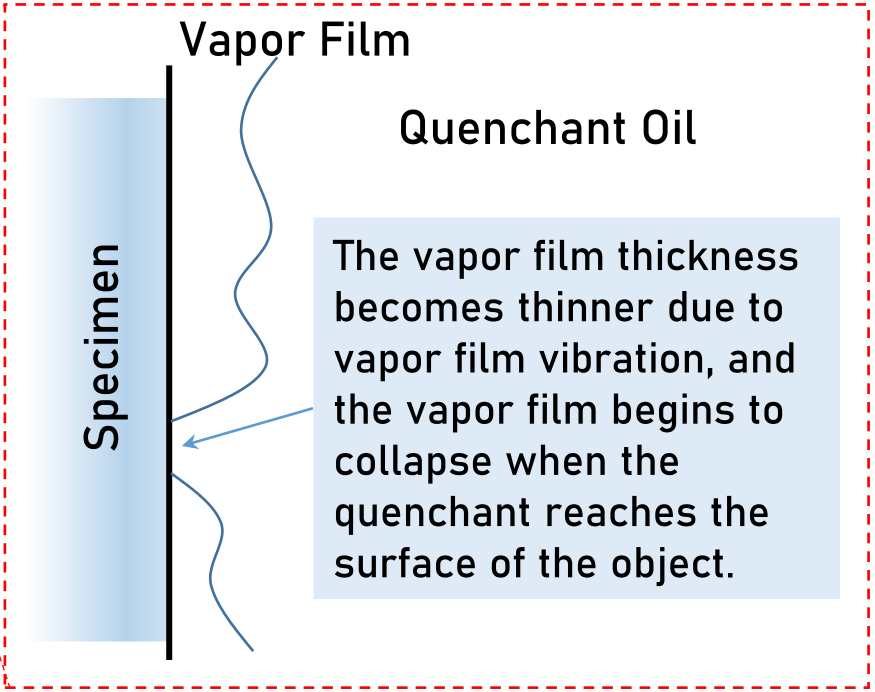
Cooling variations due to vapor film vibration





Vapor Film Vibration



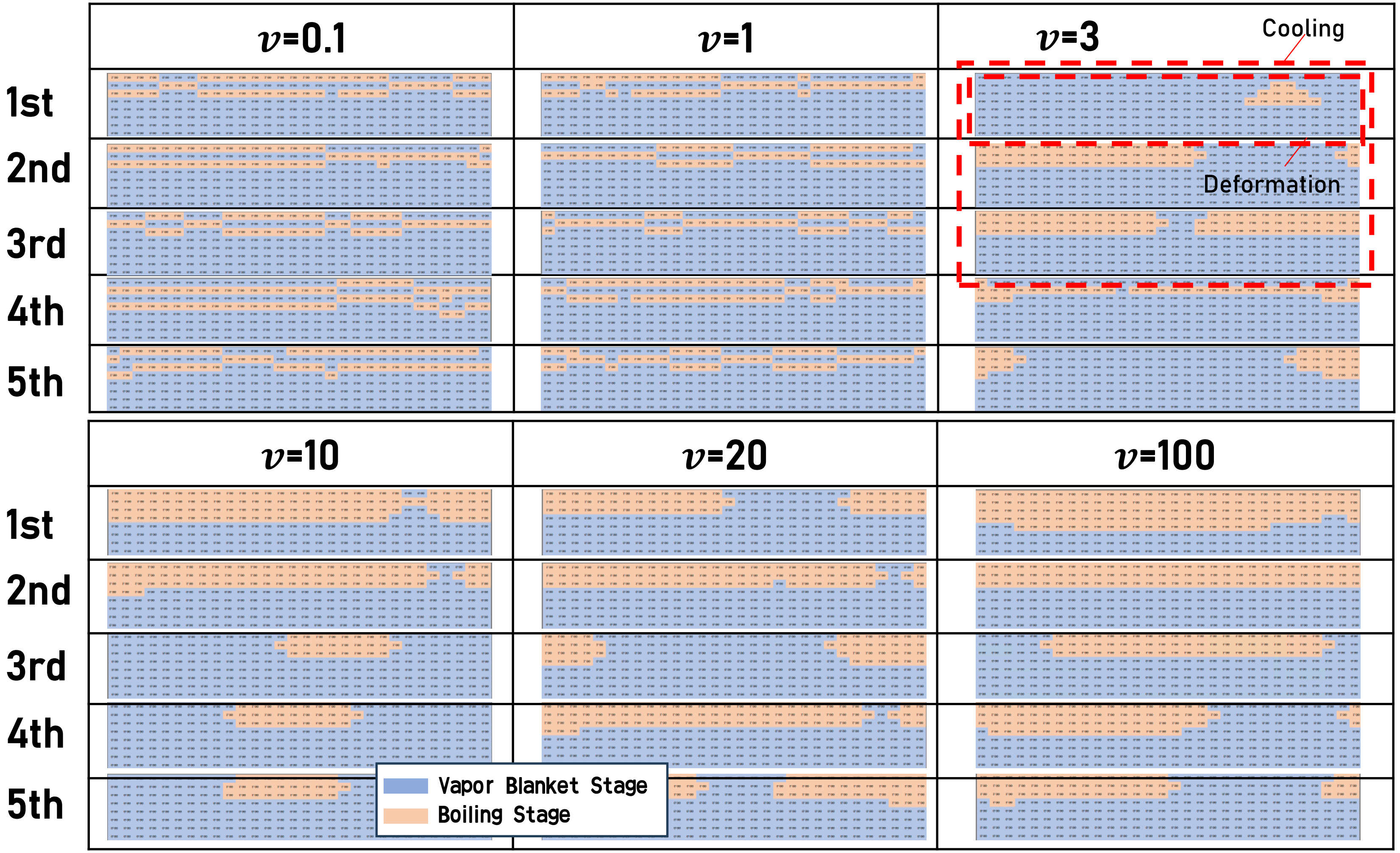
Wave propagation equation: $\frac{1}{v^2}\frac{\partial^2 u}{\partial t^2} = \Delta u$ ･･Eq.(7)

v : Phase speed
u : Vapor film thickness
t : time

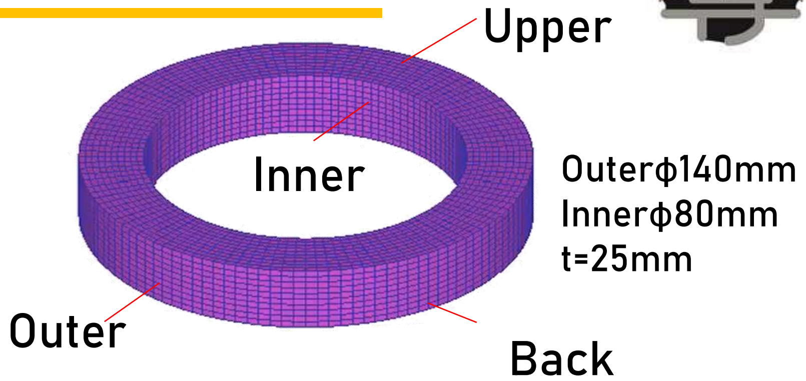
$+$

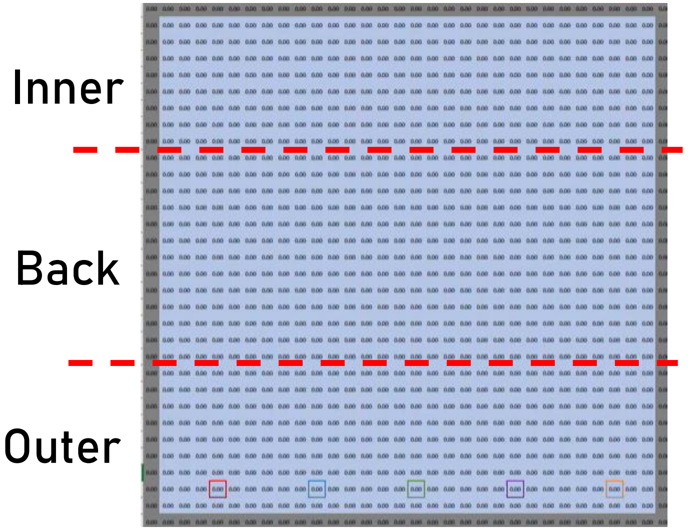
External excitation with random factor: r

Cooling variations due to vapor film vibration



Repeated changes in vapor film collapse at the outer periphery of ring when changing phase speed v

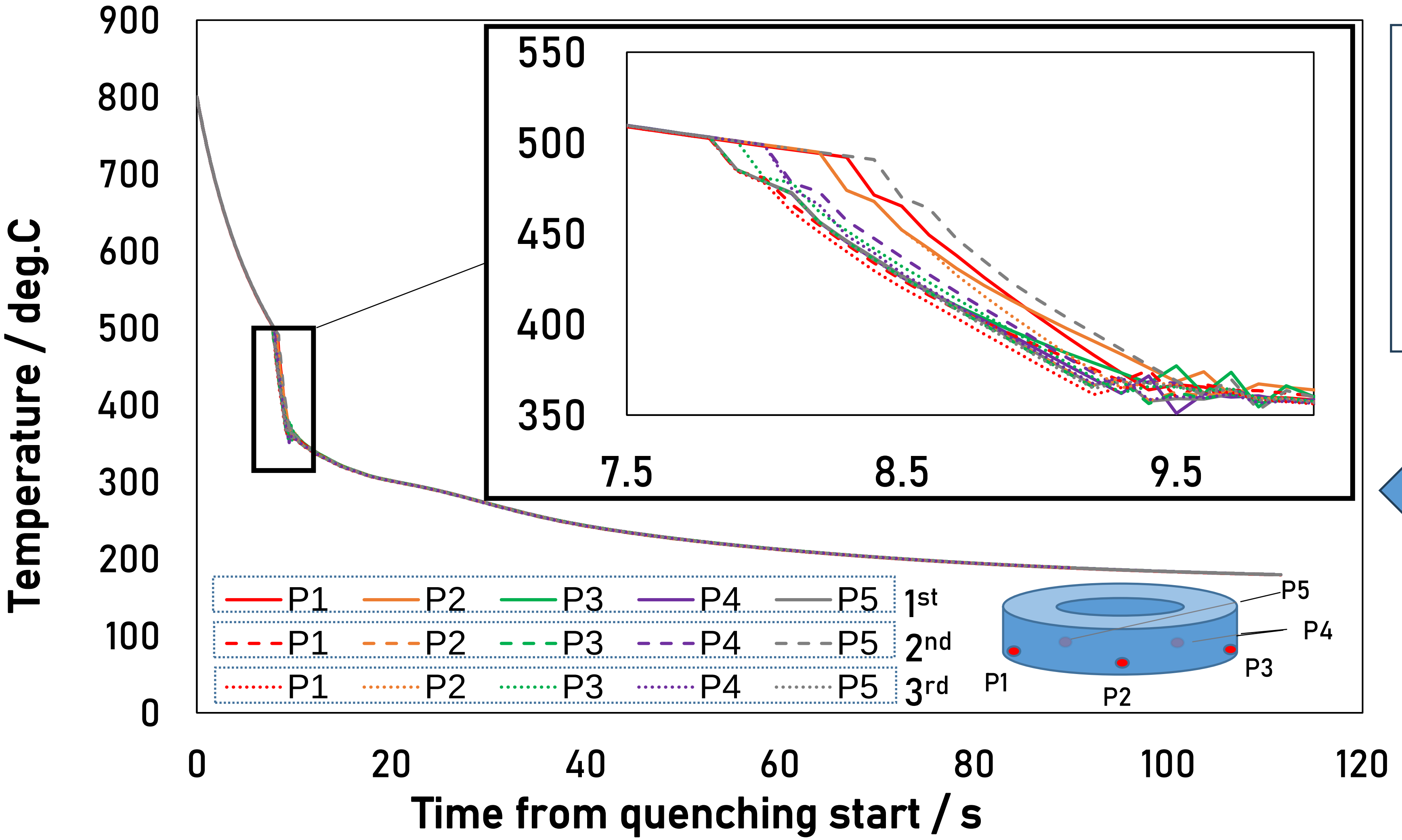




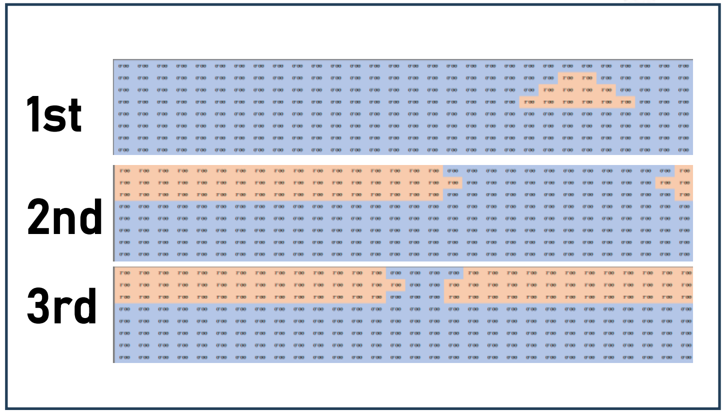
Vapor film collapses at v=3

The vapor film collapse form/repetitive change depending on the phase velocity

Cooling Curve Variation



Cooling Curve Change in Phase Velocity v=3



Vapor Film Collapse Change

Cooling curve is changed due to Vapor film collapse variation

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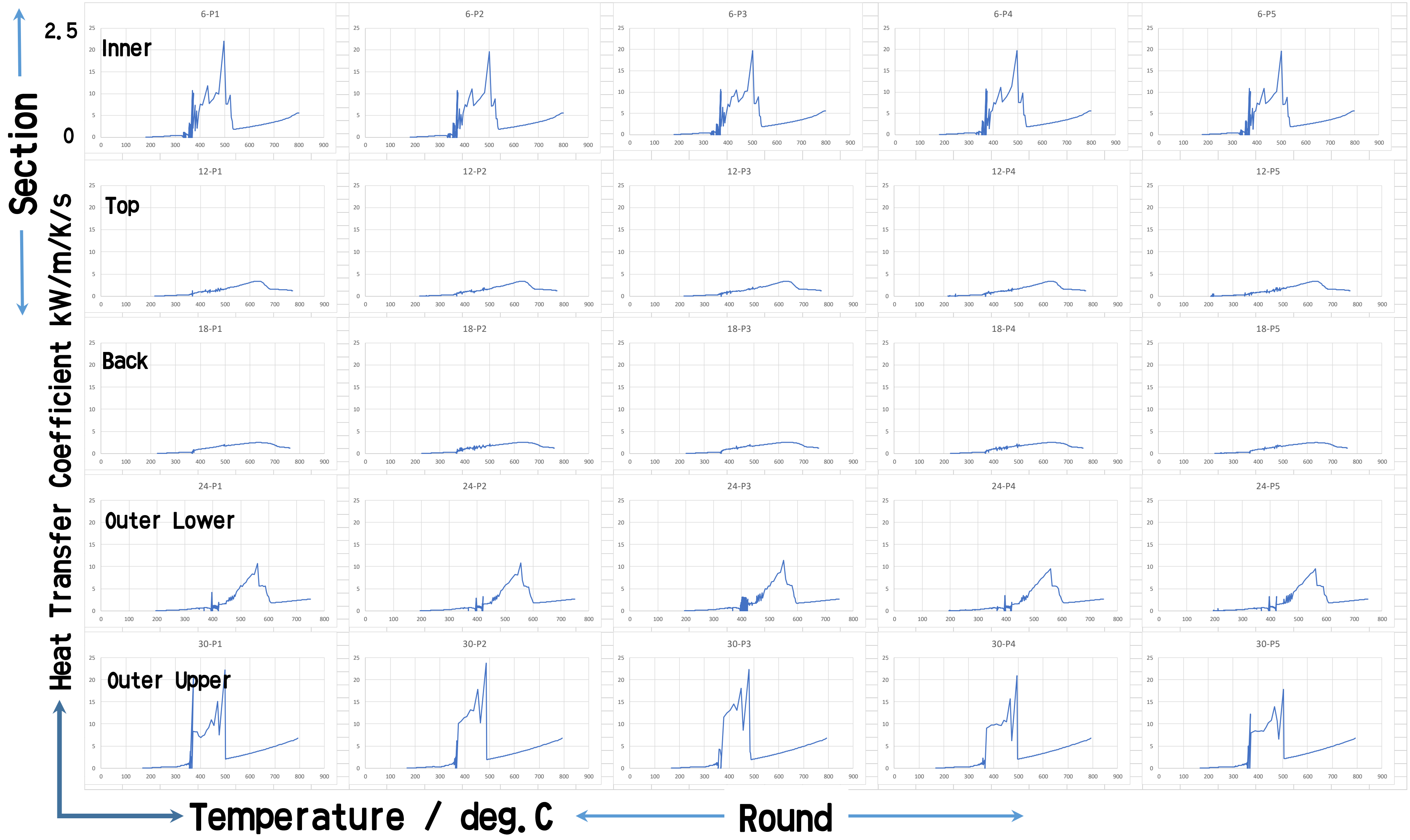
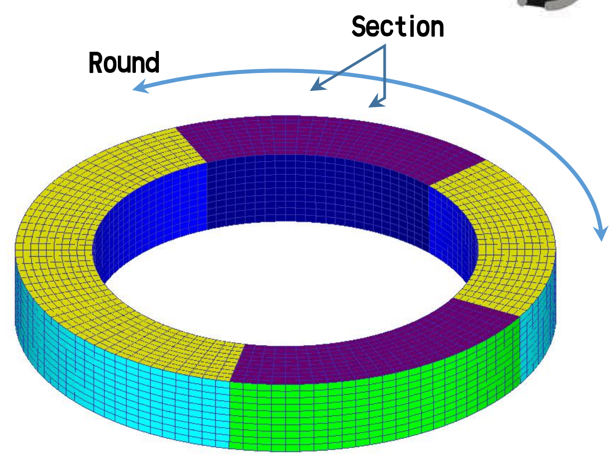
Estimate Heat Transfer Coefficient(v=3)

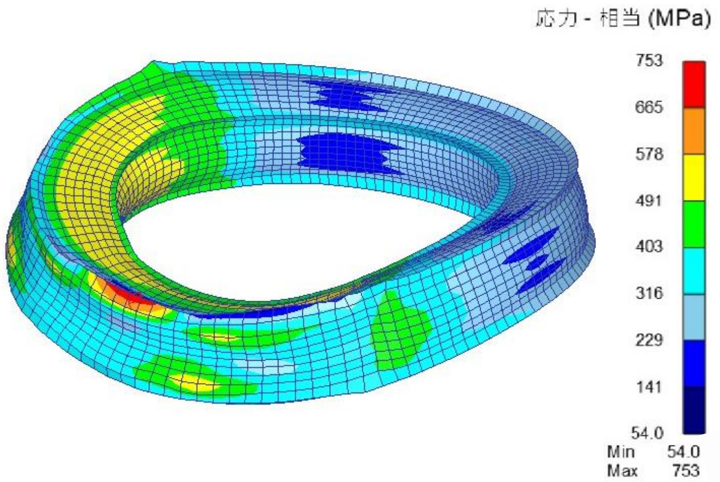




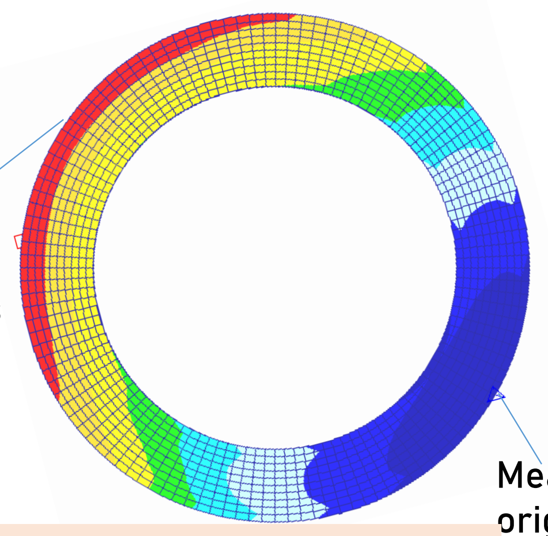
The surface was divided and a calculated heat transfer coefficient was assigned to each part.

- The heat transfer coefficient on the back side is low
- At the end of boiling stage, Vapor bubbles are generated, which causes the heat transfer coefficient to rise and fall.
- Minimum film boiling temperature is changed

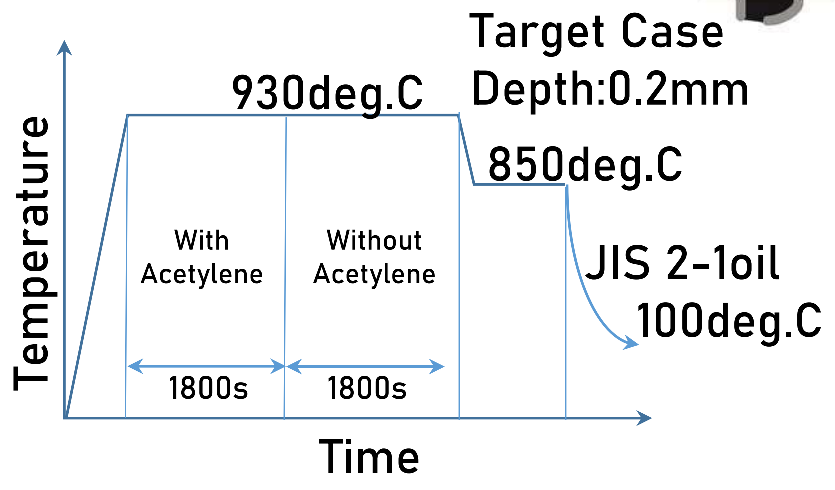
Result of Deformation



・Maximum displacement 0.3mm
(experiment under the same conditions
the back flatness was 0.3mm)



Measurement
origin



Heat Treatment Condition

・Quantitatively, the calculations are mostly accurate.
・Thermal deformation due to initial temperature unevenness affects the final product.

Calculation Condition

Slover	SFTC DEFORM-HT ver13
Nodes	14520
Elements	12000
Coating Mesh Size	0.1mm
Element Shape	Hexagon

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Conclusion

From Results

✓ Cooling variations may occur due to vapor film vibration. Heat treatment deformation occurs due to cooling variations.

✓ This method is abele to analyse repeated variations in heat treatment deformation at low cost.

Next step

We would like to consider mass production load setting. The coupling of the phase velocity v (~oil properties), vapor film excitation force r (~flow velocity, etc.) and steady fluid analysis will realize this one.

Acknowledges

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

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