HEXAGON

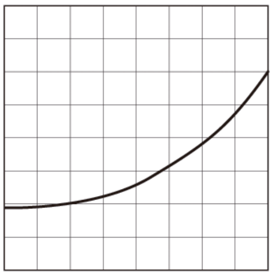
Cradle CFD

Multiphase Flow Simulation

Free Surface Flow Analysis of Airlift Pump

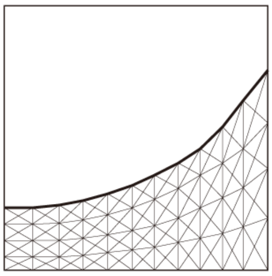
Free surface flow analysis of an airlift pump using MARS method of scSTREAM

Free Surface Flow Analysis



Interface Capturing Method

Simulates interface behavior by using advection of a function that represents the interface: MAC (Marker And Cell), Level Set, VOF (Volume Of Fluid), MARS methods.



Interface Tracking Method

Simulates the interface behavior by deforming the elements representing the interface: ALE (Arbitrary Lagrangian and Eulerian).

Free Surface Flow Analysis of an Airlift Pump

Free surface flow analysis is performed for an airlift pump, which is used for pumping of well water, hot spring, and clear well, with an interface capturing method, MARS (Multi-interface Advection and Reconstruction Solver) method.

Mechanism of Airlift Pump

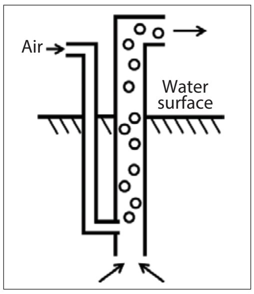


Figure 1: Airlift pump

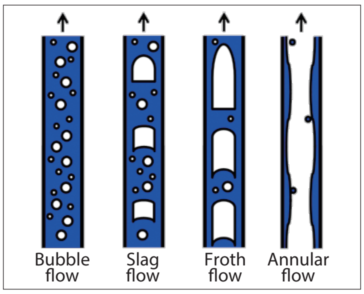


Figure 2: Types of two-phase flow

- Air is flowed into a (lifting) pipe placed under water as shown in Figure 1. Water inside the pipe is mixed with the air, becomes less dense, and is lifted upward.
- The amount of lifting is determined by an empirical formula based on the amount of the delivered air, the submergence depth, and the pump head height. Depending on the objectives, aeration may or may not be facilitated. The type of two-phase flow inside the pipe (Figure 2) needs to be understood.
- Visualization in experiment may not be possible for various reasons. Flow simulation can be effective in understanding the type of flow.

Analysis Model

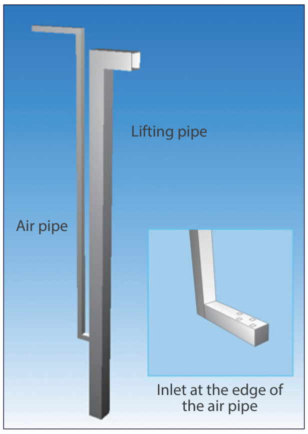


Figure 3: Pump analyzed

Lifting pipe	5 cm square
Air pipe	2 cm square
Inlets	4 houndstooth arrangement
Air flow rate	25 [L/min] every 0.1 [s] per inlet

Pump is placed 1 [m] underwater and water is pumped to the reservoir 10 cm above water surface.

Analysis Results

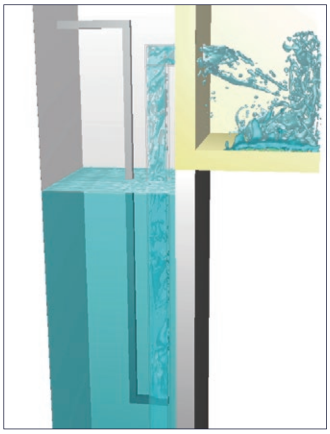


Figure 4: Isosurface

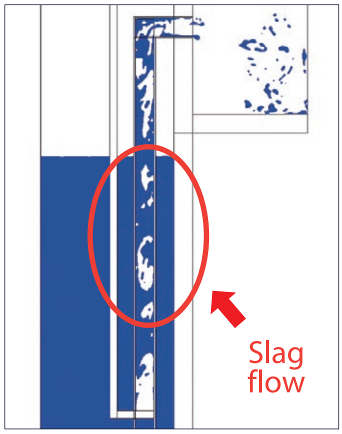


Figure 5: Gas-liquid distribution

Notes

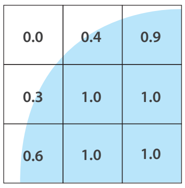
Gas-liquid interface is visualized with an isosurface (Figure 4). The analysis result simulates well how the water mixed with air is lifted and poured and splashes into the reservoir. Figure 5 shows gas-liquid distribution on the middle cross-section of the pipe. Water is shown in blue. From this figure, the type of flow inside the pipe can be predicted as a slag flow.

Analysis of Capillarity and Percolation to Soil

Capillarity and percolation to soil are analyzed with MARS method using scSTREAM

VOF (Volume of Fluid) Method

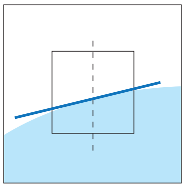
Example: Distribution of F value



Donor-Acceptor method

Stores F value strictly ▶ Interface expressed by rectangles

MARS method



Approximates interface slope by linear function ▶ High reproducibility of interface

VOF method is...

- A free surface flow analysis method that obtains the interface by solving the transport equation of F value ($0 \leqq F \leqq 1$), which is defined as the volume fraction of fluid occupying each element in the computational domain.
- Considers material properties, e.g., density and viscosity, as the 1st fluid (air, for instance) if F value is 0 and as the second fluid (water, for example) if F value is 1.

Case Study of Capillarity

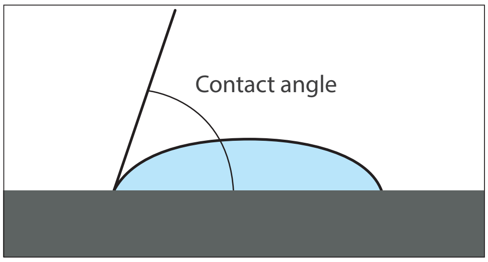


Figure 1: Contact angle

Contact angle is...

The angle between wall and free surface of the fluid (Figure 1). If contact angle is small, wall tends to get wet (hydrophilic), while if it is large, wall tends not to get wet (water-shedding).

Analysis Results

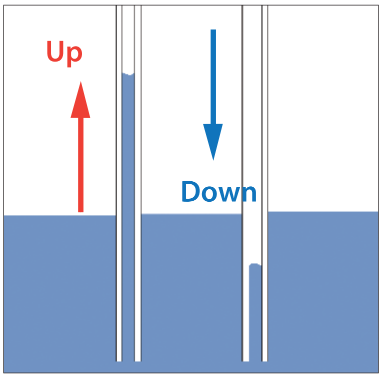


Figure 2: Capillary hydrophilic wall with plates of contact angle 60° (left) and water-shedding wall with plates of contact angle 120° (right)

By capillarity, water rises in between the plates that have hydrophilic surfaces, and falls in between the plates that have water-shedding surfaces. Fluid behavior differs greatly depending on contact angle.

Percolation to Soil

Analysis Model (Soil Cross Section)

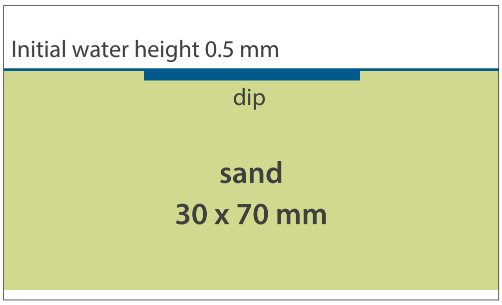


Figure 3: Analysis model

Depth	30 mm
Width	70 mm
Dip	Depth 1 mm
Void fraction	0.15 (sand, resin)
Contact angle	90° (resin)
Darcy coefficient	5×10^{-10} m^2 (Equivalent of permeability when void fraction is 0)
Initial condition	Uniform water height of 0.5 mm (Depth 1.5mm for the dip)

Analysis Results

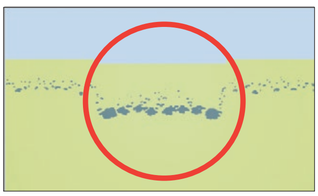


Figure 4: Water percolation to sand

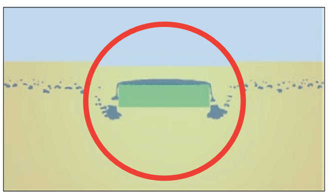


Figure 5: Water percolation to sand (with resin installed)

Notes

Figure 4 is the analysis result after 2 seconds. The apparent percolation velocity is approximately 10 [mm/s] in the middle section. Figure 5 is the analysis result for the case where resin, whose Darcy coefficient is lowered by two digits to improve the water retention of sand, is installed at 5 [mm] deep. Prevention of water percolation by the resin is well simulated.

SC/Tetra

Analysis of a Water Ride

Motion of the water ride is simulated with VOF method and overset mesh using SC/Tetra

VOF Method and Overset Mesh

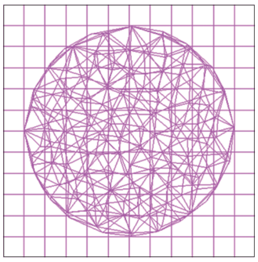


Figure 1: Overset mesh

- In the latest fluid simulation analysis software, a combination of VOF and other analysis functions are used to analyze free surfaces. This enables an analysis of a free surface flow with moving objects.
- Overset mesh (overset grid) is a method to overlay elements of moving region and static region. The program will be simpler and the calculation will be stable because the elements do not need to be regenerated.

Analysis Descriptions

Analysis Model

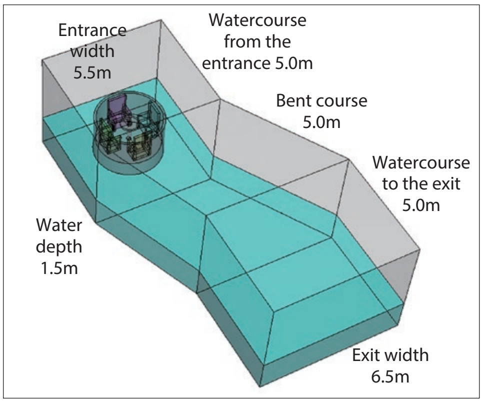


Figure 2: Bent watercourse

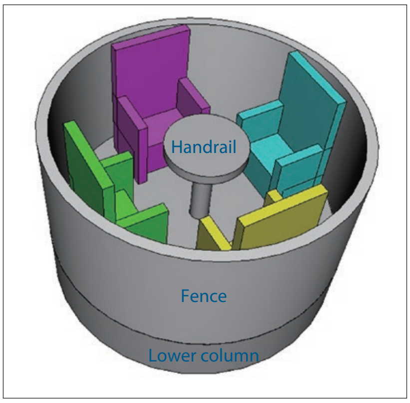


Figure 3: Ride vehicle

Passenger	4 Adults
Seat	4 (86 [kg] each to account for passengers)
Diameter	3 [m]
Density	360 [kg/m^3] (Lower column and fence)
Motion	6 DOF (6 Degree of freedom)

The ride translates and rotates due to the forces exerted by water flow.

Analysis Results

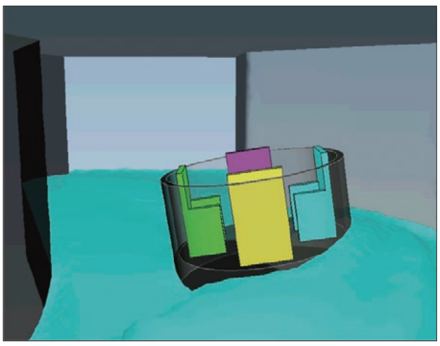


Figure 4: 3 seconds after the ride vehicle went in motion (speed 6 km/h)

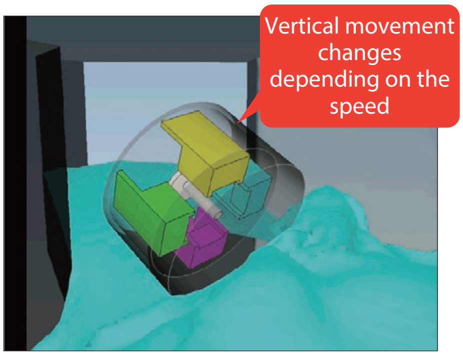


Figure 5: 3 seconds after the ride vehicle went in motion (speed 7 km/h)

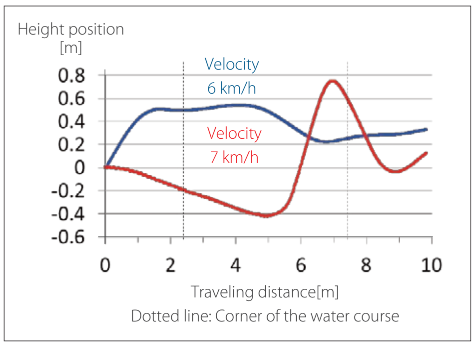


Figure 6: Relation between the height position of the vehicle and the traveling distance

Notes

Figure 4 shows the analysis result of the ride vehicle traveling on the water at 6 [km/h]. The ride vehicle pitches and rolls. Figure 5 shows the analysis result at 7 [km/h]. The vehicle does not capsize; however, it careens freely and the safety of the passengers cannot be guaranteed. Figure 6 shows the relation between the height of the vehicle on the water and the distance traveled. The height difference is 0.54 [m] after the vehicle travels 10 [m] at 6 [km/h], and it reaches 1.2 [m] at 7 [km/h]. At 6 [km/h], the vehicle strongly pitches and rolls, and 6 [km/h] is sufficient speed to make the water ride fun and exciting.

Sloshing in an Oil Tank

Sloshing in an oil tank is analyzed using scSTREAM

Case study: Analysis of an Oil Tank

Analysis Model

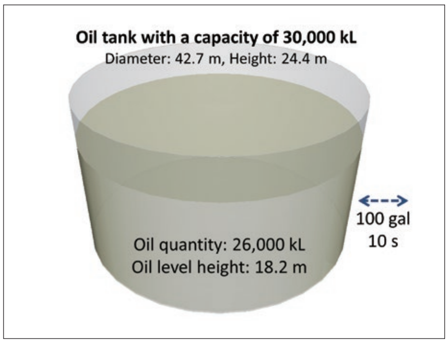
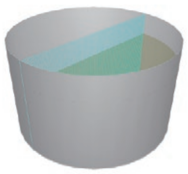


Figure 1: Oil tank with a capacity of 30,000 [kL]

Oil reserves	26,000 [kL] (Density 740 kg/m^3, viscosity 0.0026 Pa·s, surface tension coefficient 0.020 N/m)
Roll	• 100 gal (magnitude 5, acceleration 1 m/s^2) • 10 seconds continuous • 5-second period as a long-period oscillation
Number of mesh elements	1,306,800 (structural mesh)

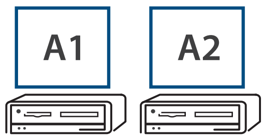
- Sixty seconds in real time are analyzed by MARS (Multi-interface Advection and Reconstruction Solver) method
- Time step is set automatically such that the Courant number does not exceed 0.9

Consideration on Reduction in Computation Time



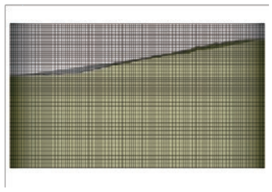
(1) Symmetry plane setting

The number of elements is reduced to 653,400 by applying a symmetry plane as shown in the figure above. Computation time is shortened by 52%.



(2) Parallel computation

With 2-parallel computation, computation time is further shortened by 47%.



(3) Partial rough gridding

Grid is made rougher below the oil surface at the time when its height difference is the maximum. The number of elements is reduced to 505,296, and computation time is reduced by 23%.

(4) 1-fluid setting

One-fluid setting of Solver can be used. Computation speed can be improved by 30%.

Computation time reduced from **4 hours** to **0.5 hours**

Reduction by **86%** from the initial setup

Analysis Results

Figure 2: The maximum oil surface height. Left: 5 sec. period (t=13 [sec.]), middle: 4 sec. period (t=15 [sec.]), right: 2 sec. period (t=17 [sec.])

Notes

Figure 2 shows the analysis results with 100 [gal] roll and different roll periods. Figure on the left is the capture of the maximum surface height for the 5-second period case, in the middle is for the 4-second period case, and on the right is for the 2-second period case. It can be seen that a resonance occurs for the 5-second period case, which is close to the characteristic period of the sloshing.

SC/Tetra

Analysis of Molten Solder

Process of reflow soldering is analyzed using SC/Tetra

Case study: Analysis of Molten Solder

Analysis Model

Solder cream is applied to the two lands on the board. A rectangular chip resistor is attached.

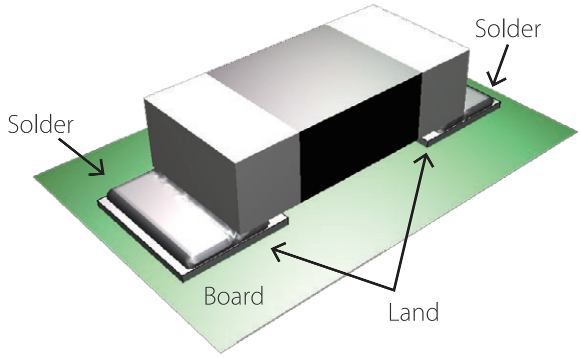


Figure 1: 0402-size chip resistor

Chip resistor	Length 0.4 mm Width 0.2 mm
Viscosity of molten solder	Variable ~ 0.020 ~ 100 Pa·s to express melting
Density of molten solder	8,000 kg/m^3
Surface tension	0.40 N/m
Contact angle with land and chip resistor	30°

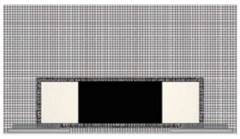


Figure 2: Overset mesh

- Overset mesh is used in the moving overlap region that surrounds the chip resistor and each element in the static region.
- Motion of the chip resistor is given 6DOF (6 degree of freedom). The chip resistor translates and rotates with consideration on the force from molten solder by solving the equations of motion.

Analysis Results

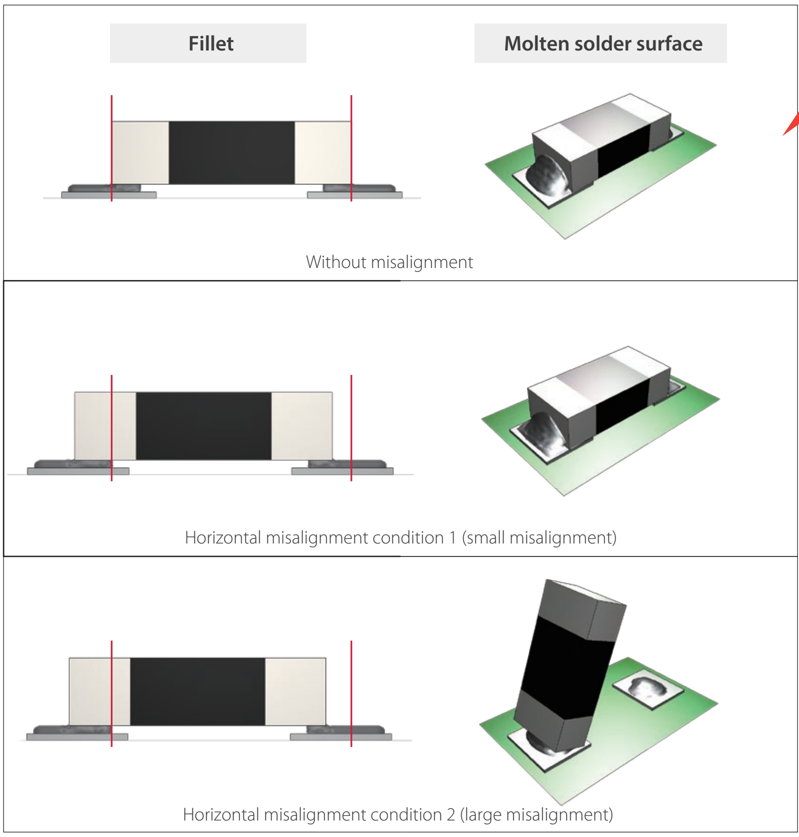


Figure 3: Molten solder analysis results (without misalignment [top], horizontal misalignment condition 1 [middle], horizontal misalignment condition 2 [bottom])

Formation of molten solder surface fillets are well simulated at both ends of the chip resistor

Notes

From the result of horizontal misalignment condition 1 in Figure 3, slight horizontal misalignment does not affect the formation of the solder fillets. The phenomenon that causes electronic parts to stand as in the result of horizontal misalignment condition 2 is called the Manhattan phenomenon, likened to the high-rises in New York City.

SC/Tetra

Analysis of a Sand Separator

Separation of water and sand is analyzed with Particle Tracking Method using SC/Tetra

Particle Tracking Method

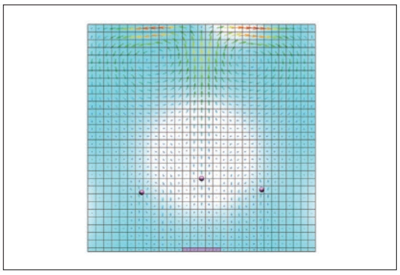


Figure 1: Two way coupling

In Particle Tracking Method, fluid is analyzed as a continuous phase by using grid-patterned elements as shown in Figure 1 (Euler method), while particles are tracked individually as dispersed phase (Lagrange method). Fluid and particles are analyzed interactively.

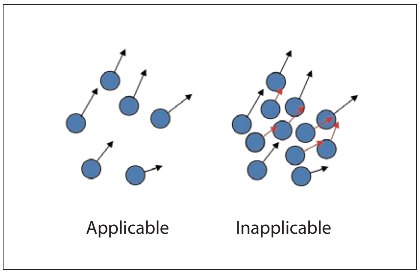


Figure 2: Application of the particle tracking method

In Particle Tracking Method, particles are considered as point masses; this means that the method should not be applied for an analysis where contact or collision of particles is dominant as shown in Figure 2.

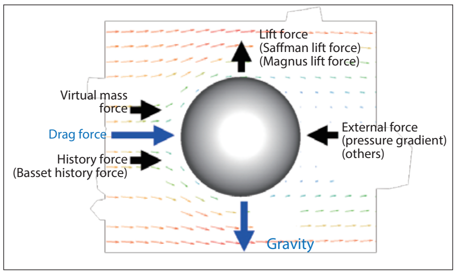


Figure 3: Forces acting on a particle in fluid

When density of particle is greater than that of fluid, the drag force and gravity are the main forces acting on the particle. Because the drag force is calculated assuming that the geometry of particle is a sphere, a care should be taken for sand or dust, which is not usually a sphere, or for droplet, which changes shape.

Analysis of a Sand Separator

Analysis model

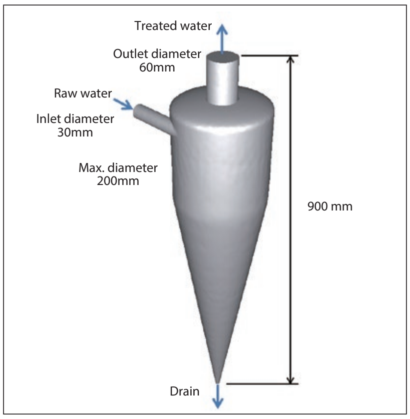


Figure 4: Sand separator

Analysis results

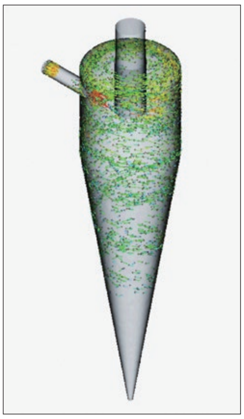


Figure 5: Particle behavior

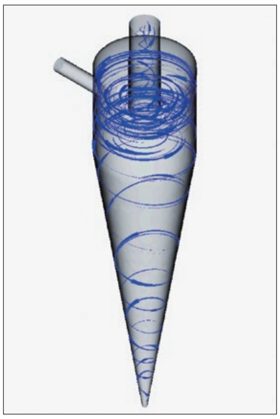


Figure 6: Streamlines

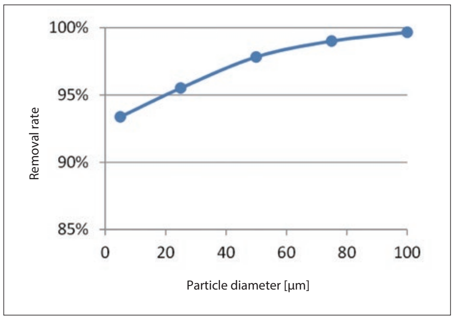


Figure 7: Variation of the sand removal rate depending on the particle diameter

Sand separator

Separates sand from water using centrifugal force. Ratio of density of sand and water is approximately 2.5, which is much smaller than that of sand and air. Separating sand from water is difficult.

The inflow rate of raw water is fixed at 2.8 [m^3/h]. Approximately 3% of the water flows out the drain. Next, 100 sand particles with a fixed diameter and a density of 2,500 kg/m^3 are injected into the inlet with the raw water every 0.1 seconds. The separation state is analyzed using the particle tracking method for 30 seconds. The sand removal rate is calculated by dividing the number of sand particles going out the drain by the total number of particles going out the drain plus the number in the treated water.

Notes

- Figure 5 shows the analysis result of the behavior of sand particles with a diameter of 100 [μm]. The behavior of the particles is shown using velocity vectors until 7 seconds after the analysis starts. The particles flow in with the raw water, move downward along the separator wall, and flow out with the drain.
- In Figure 6, streamlines of the water are expressed with arrows. The swirl flow occurring in the separator is clearly simulated.
- Figure 7 shows the variation of the sand removal rate depending on the particle diameter, for 5, 25, 50, 75, and 100 μm diameters. The smaller the particle diameter is, the lower the removal rate becomes.

Analysis of Snowbreak Trees

Snowbreak trees are analyzed with Particle Tracking Method using scSTREAM

Analysis Descriptions

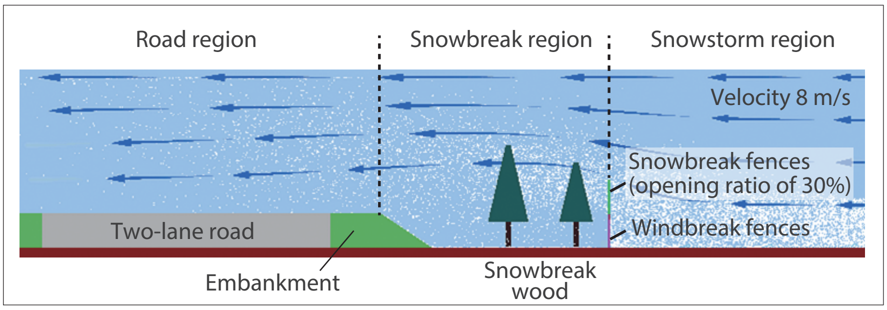


Figure 1: Snowbreak trees along the road

Inflow air	Power-law (flat land) profile with velocity 8 [m/s] (reference height 10 [m]) and -20 [℃]
Snow particle	• Density 200 [kg/m^3], diameter 100 [μm] • Uniform inflow from ground to 3 [m] high • Parcel approximation with 1,000 effective particles
Repulsion coefficient	0.5 (applied to boundary faces including ground surface and windbreak fence)
Duration	8 seconds

Analysis Model of a Needle Leafed Tree

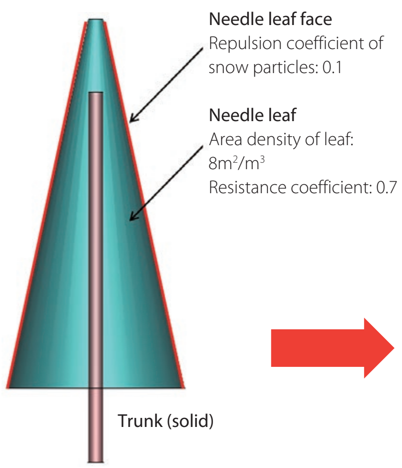


Figure 2: Needle leaf tree (Cross section)

Leaf area density	8 m^2/m^3
Resistance coefficient	0.7 pressure loss region
Repulsion coefficient	0.1 for snow particle
Tree arrangement	Two lines of needle-leaf trees with 4-meter gap in zigzag pattern (narrow-band region)
Setting of needle-leafed tree	• Nursery period 15 years after planting • Rearing period 15 years after nursery period • Conservation period 30+ years after planting

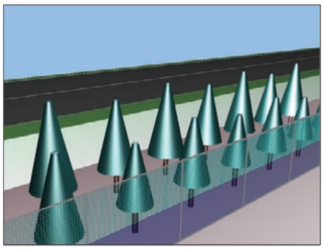


Figure 3: Nursery period (tree height 4.5–6.0m), windbreak fence (2m), snowbreak fence (2m)

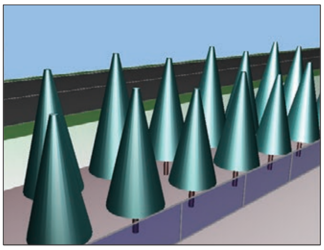


Figure 4: Rearing period (tree height 6.5–8.0m), windbreak fence (2m)

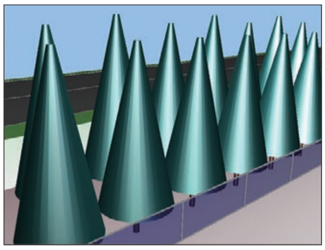


Figure 5: Conservation period (tree height 9.0–10m), windbreak fence (2m)

Analysis Results

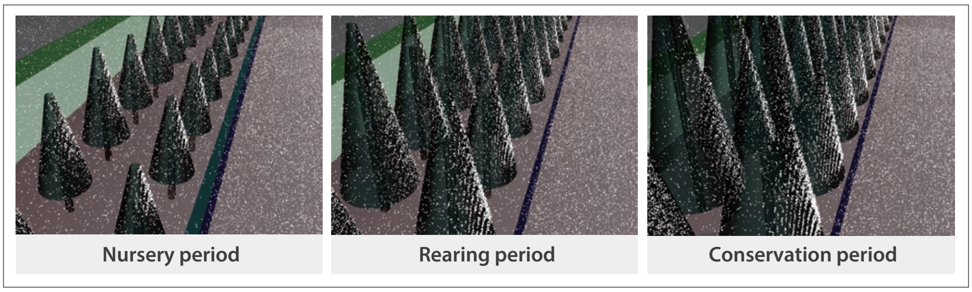


Figure 6: Snow particle behavior

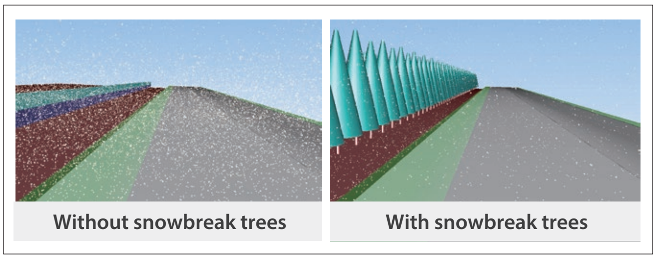


Figure 7: Road visibility

Notes

As the snowbreak trees grow, the number of snow particles increases in the snowbreak region and decreases in the road region, and the snowbreak effectiveness improves.

Analyses of Spray Air Nozzle and Spray Combustion

Phenomena are analyzed with consideration on evaporation and volatilization using Particle Tracking Method in scSTREAM

Analysis of a Spray Air Nozzle

Using Particle Tracking Method, a spray air nozzle for cooling high-temperature gas with water droplets is analyzed.
Two spray conditions are compared.

Evaporation Model of Water Droplet

Analysis Settings

Inflow high-temperature gas	500 [°C]
Spray air	27 [°C]
Shape	2D axisymmetric (chamber, nozzle)
High-temperature gas velocity	25 [m/s]
Spray air velocity	40 [m/s]
Wall	No-slip, adiabatic

Analysis Results

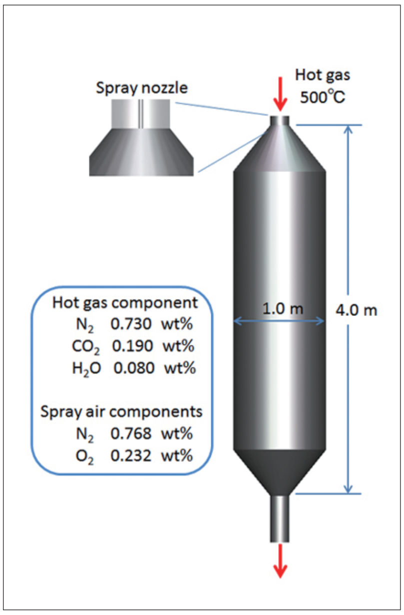


Figure 1: Spray air nozzle

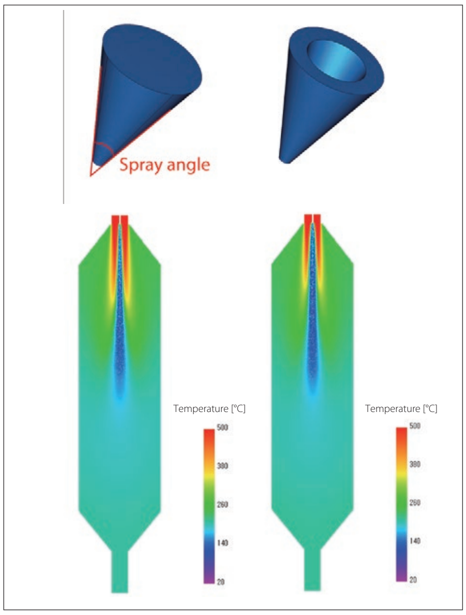
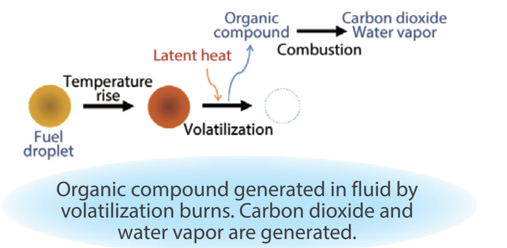


Figure 2: Temperature distribution (7 sec.)
Full-cone (left), hollow-cone (right)

Analysis of Spray Combustion of Fuel Droplets

Spray combustion of fuel droplets is analyzed with Particle Tracking Method.

Spray Combustion Model of Fuel Droplets



Analysis settings

Fuel droplet	Sauter mean diameter 20 [μm] (Nukiyama-Tanazawa distribution for diameter distribution)
Spray flow rate	0.005 kg/s (Parcel approximation 10,000 s^{-1})
Spray velocity	15 m/s
Spray pattern	Hollow cone Spray angle 110 - 120°

For 1 second, only air and spray air are flowed in. The fuel spray begins after 1 second.

The latent heat of the fuel droplets is 200 [kJ/kg], and n-Decane is used for the constants of the Antoine equation.

Analysis Results

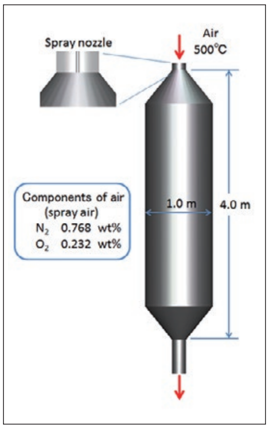


Figure 3: Combustion chamber

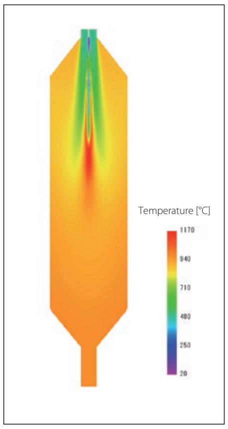


Figure 4: Behavior of fuel droplets and temperature distribution (8 sec.)

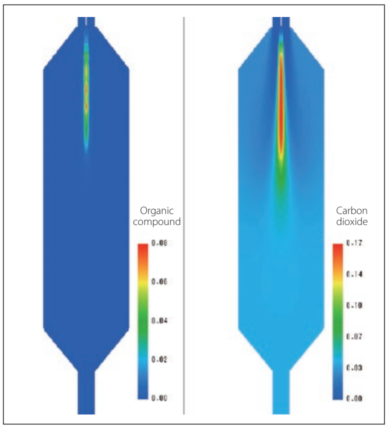


Figure 5: Mass fraction distribution of combustion gases (8 sec.), organic compound (left), carbon dioxide (right)

Notes

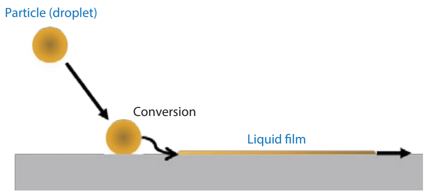
From the analysis result of spray air nozzle, it can be seen that hollow cone spray is cooling the gas slightly faster in comparison. From the analysis result of spray combustion, it can be seen that temperature of the combustion gas in the chamber rises due to combustion of the fuel droplets.

Analyses of Spray/Painting Nozzle and Single-Wafer Cleaner

Liquefaction of particles is analyzed using scSTREAM and SC/Tetra

Analysis of Spray/Painting Nozzle (SC/Tetra)

Liquid Film Model



Method to analyze liquid film moving along wall by considering material property (density and viscosity) and thickness of film formed by liquefaction of particles on wall. Has a small calculation load because it does not consider surface tension or contact angle.

Analysis Results

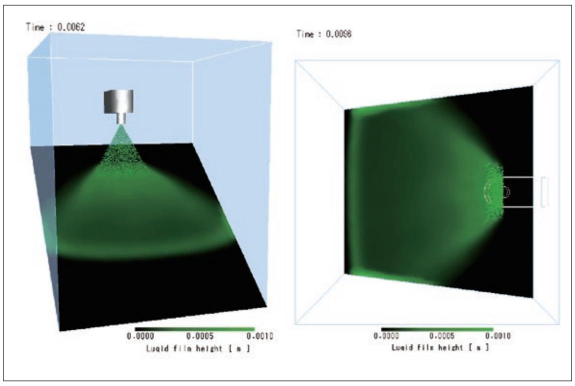


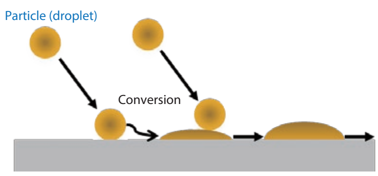
Figure 1: Analysis result (left: view from the side of the nozzle, right: view from above the nozzle)

Plate	50 mm× 40 mm Placed at an angle
Spray particle	Diameter 100 [μm] Painted by spraying from the nozzle and liquefying on the plate
Thickness of painted film	In the order of 1 [mm] Particles are sprayed in a flat shape with long axis 30°, short axis 10°

Virtually uniform painting of the liquid can be confirmed

Analysis of Semiconductor Single-Wafer Cleaner (scSTREAM)

Method to Use Free Surface Flow Analysis in Combination



Particles are converted to liquid when they adhere to wall or liquid surface. The particles converted to liquid are vanished and no longer tracked. Since the method considers surface tension and contact angle, it can analyze breakups and cohesions of liquid; however, calculation load is large compared to the liquid film model.

Analysis Results

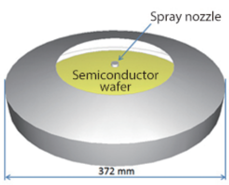


Figure 2: Single-wafer cleaner

Spray nozzle	Particle diameter 50 [μm] (1-fluid nozzle)
Spray flow rate	0.50 [kg/s] 30 L/min
Spray velocity	15 m/s
Material	Pure water (cleaning water)
Contact angle	50°

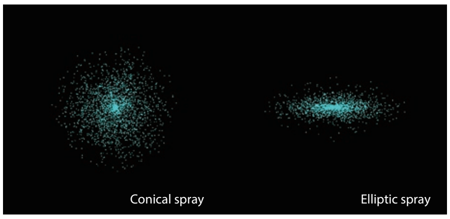


Figure 3: Conical spray with spray angle 30° (left), 5° (right)

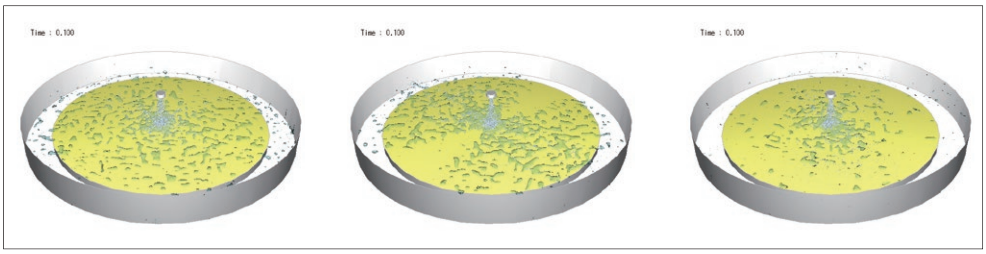


Figure 4: Cleaning water after 100 seconds. Conical spray (left), elliptical-cone spray (middle), elliptical-cone spray 2,500 rpm (right)

For elliptical-cone spray, higher rotation speed of the wafer for better cleaning efficiency spreads cleaning water in the circumferential direction.

Notes

Using scSTREAM and SC/Tetra, liquefaction of particles are simulated with Particle Tracking Method.

SC/Tetra

Analysis of an Electrostatic Spray Gun

An electrostatic spray gun is analyzed with Particle Tracking Method using scSTREAM

Analysis of an Electrostatic Spray Gun

Analysis Model

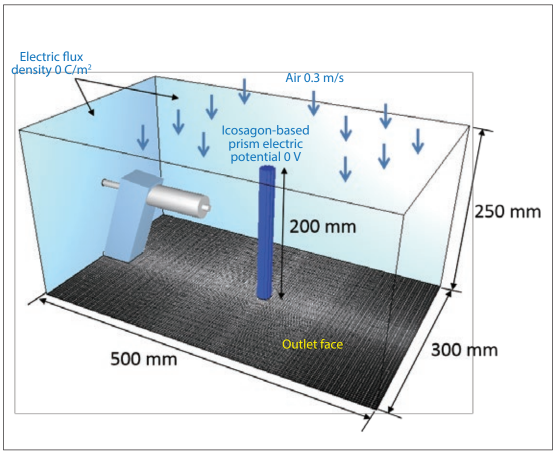


Figure 1: Coating booth

Coating booth	500 mm × 300 mm × 250 mm
Icosagon-based prism	• 20 [mm] widex 200 [mm high icosagon-based prism • Located 100 [mm] away from the tip of the electrostatic spray gun • Electric potential is 0 V (Ground)
Air velocity	• Flows into the booth from the ceiling with a uniform velocity of 0.3 [m/s] • The floor of the booth is the outlet (like a grating) Removes paint particles that have not adhered to the prism
Electric flux density	0 [C/m^2] (All walls of the booth including the ceiling and the floor)
Relative permittivity of air	Relative permittivity of air 1.000586

Analysis Results

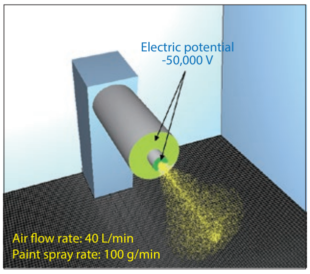


Figure 2: Electrostatic spray gun

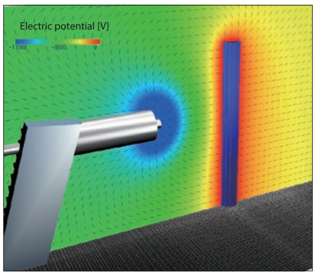


Figure 3: Electric potential distribution

Air flow rate	40 [L/min] (Nozzle diameter 10 [mm])
Paint spray rate	100 [g/min] (Density of the paint is 1000 [kg/m^3])
Diameter of paint particle	50 [µm]
Electric potential of nozzle tip	-50,000 V

Paint particles that adhered to the icosagon-based prism are vanished and no longer tracked

Converted to coating thickness by sedimentation

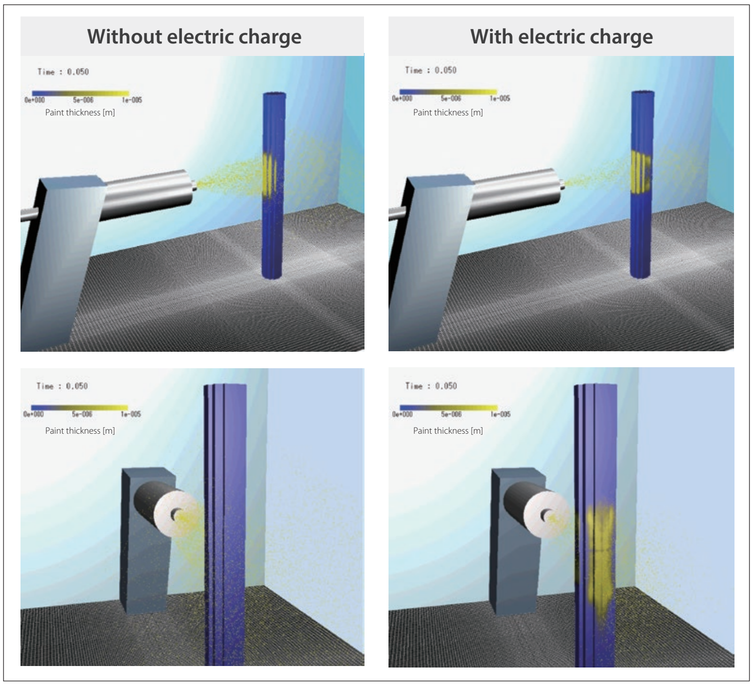


Figure 4: Analysis result (0.05 sec.)
Paint distribution in front (top), paint distribution in back (bottom)

Notes

The coating efficiency of the paint spray process is calculated from the number of paint particles that adhere to the icosagon-based prism and the number of particles sprayed from the nozzle. The efficiency is 59.6 % without electric charge on the paint particles. It is 84.5 % with electric charge on the particles. The effect of electrostatic painting is well simulated.

Analysis of a Defroster

Dew condensation and evaporation on room window and wall are analyzed using scSTREAM

Analysis of an Electric Defroster

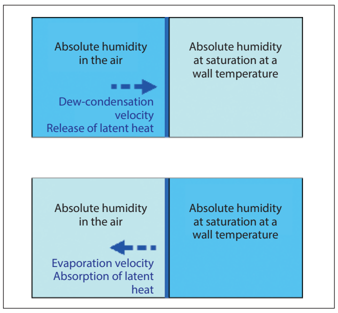


Figure 1: Dew condensation rate

Defroster is...

Function to remove car window frost caused by dew condensation.

Dew condensation analysis...

- Treats water vapor as a variable in the fluid analysis of the gas phase
- As shown in Figure 1, when the absolute humidity in the air is greater than the saturated absolute humidity at the wall temperature, dew condensation rate [kg/(m²·s)] rises and heat of 2,500 [kJ/kg] corresponding to the latent heat is generated.
- When the absolute humidity in the air is smaller than the saturated absolute humidity at wall temperature, evaporation rate, which is the negative dew condensation rate, rises and the heat corresponding to the latent heat is absorbed.

Analysis Model

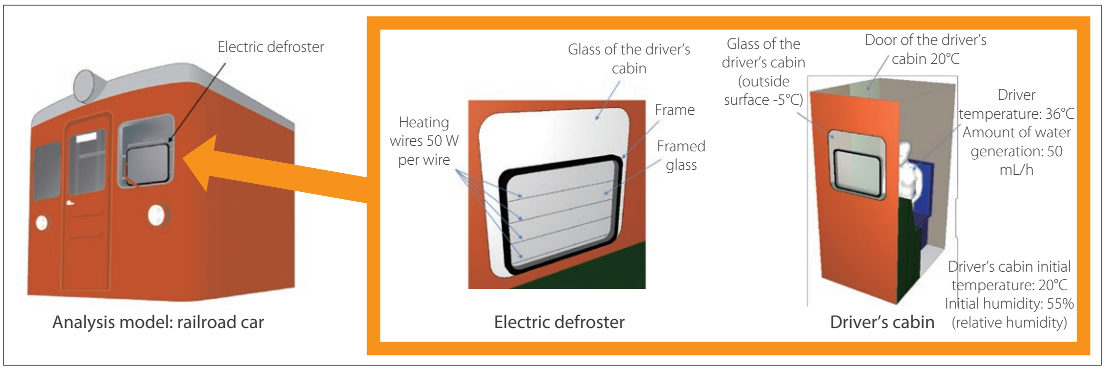


Figure 2: Railroad car

- Assume double-glazed glass window.
- Four heating wires are used and they start heating 90 seconds after the simulation starts. The heating rate reaches 100 W per wire in 10 seconds, and it is maintained thereafter.

Analysis Results

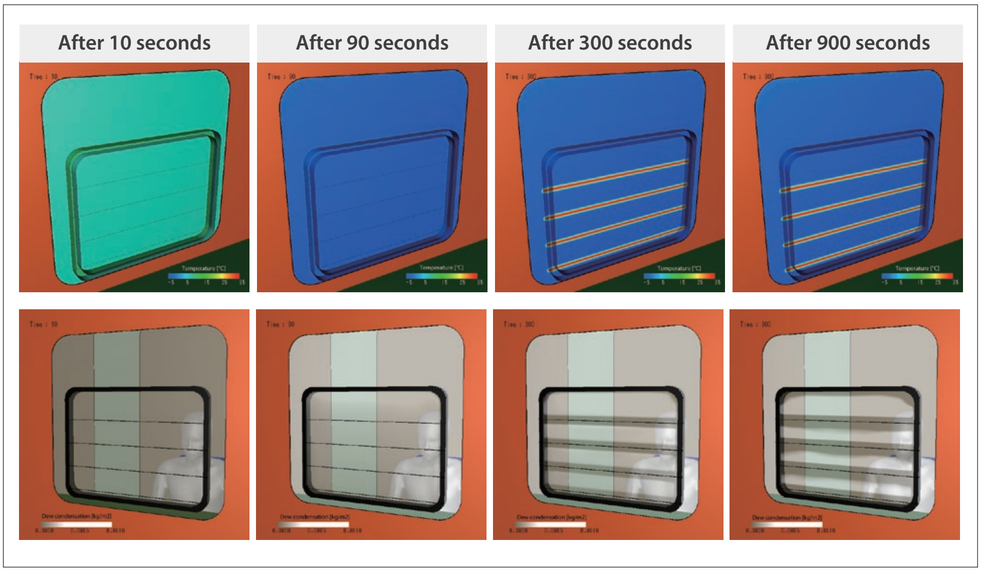


Figure 3: Temperature distribution of glass of the driver's cabin (above), dew condensation distribution (below)

Analysis target	Driver's cabin
Surface temperature	36 °C
Amount of water generation	9.0×10^{-6} kg/(m² s) (50 mL/h)
Surface temperature	• -5 [°C] (outside drive's cabin window) • 20 [°C] (driver's cabin door) • The rest is adiabatic
Initial temperature	20 [°C] (driver's seat)
Initial humidity	55% (relative humidity) Consider buoyancy due to temperature difference

Notes

Dew condensation occurs on the glass of the driver's cabin window after 90 seconds after the start of calculation. Dew condensation is being removed as heat is generated from the heating wires.

scSTREAM

Drying Laundry in a Bathroom

Dew condensation and evaporation analysis is performed with consideration on moisture absorption and desorption properties of solid

Setting of Absorption and Desorption Properties

Absorption/desorption properties are...

Amount of moisture to change humidity (absolute humidity) of a solid and amount of moisture to change temperature of a solid.

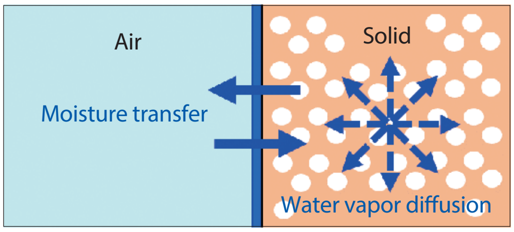


Figure 1: Humidity in a solid

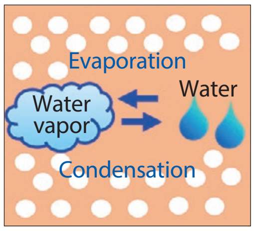


Figure 2: Moisture absorption and desorption in a solid

As shown in Figure 1, assume a solid in a dry state with voids (porous medium). Moisture in solid transfers when water permeates in the solid and water vapor diffuses. At the same time, a phase change between water vapor and water occurs inside the solid as shown in Figure 2. Since heat generation and absorption corresponding to latent heat due to the phase change affects the phenomenon, transfer of moisture and heat in the solid requires to be simulated in a coupled analysis. The setting of absorption/desorption properties of solid is needed to perform this coupled analysis.

Analysis of Laundry Drying System in a Bathroom

Analysis Model

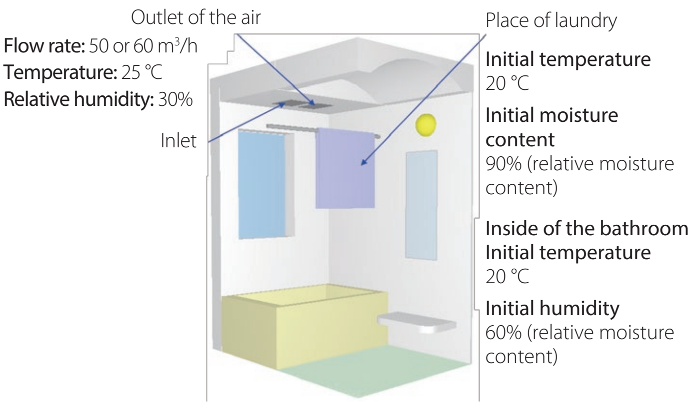


Figure 3: Laundry drying system in the bathroom

Laundry	126 cm long × 60 cm wide × 1cm thick, hung from the horizontal bar near ceiling
Porosity	0.4 (dry state)
Density	1.30 kg/m^3
Specific heat	1.15 kJ/(kg•K)
Thermal conductivity	0.086 W/(m•K)
Moisture conductivity	5.0×10^{-6} kg/(m•s (kg/kgDA))[*1]
Amount of moisture to change absolute humidity	5.0×10^3 kg/(m^3 (kg/kgDA))[*1]
Amount of moisture to change temperature	2.5 kg/(m^3 K)

[*1] DA: Short for Dry Air
kg/kgDA: Unit of absolute humidity

Analysis Results

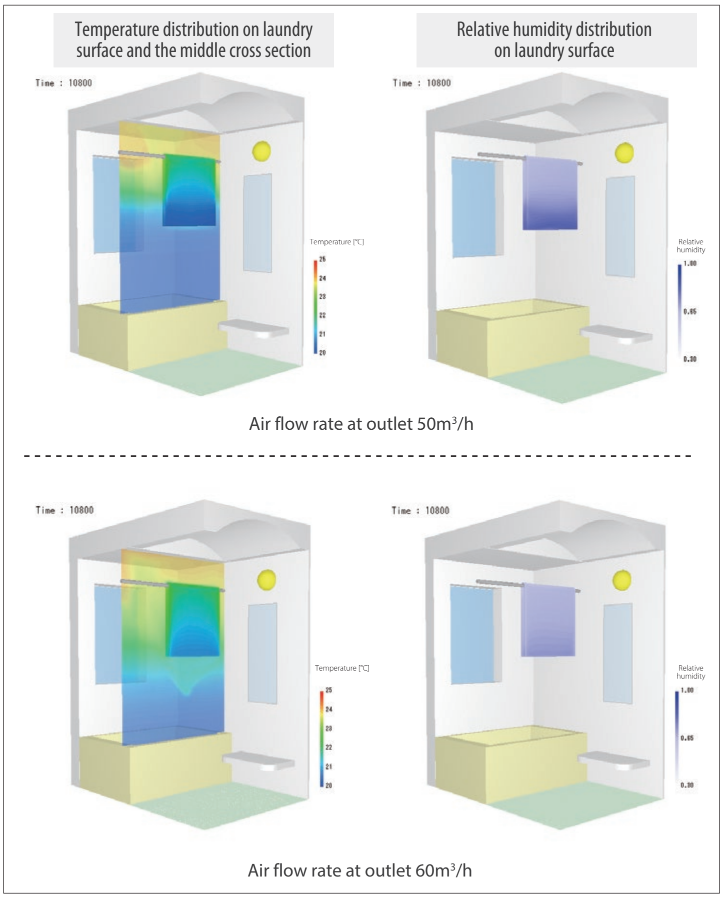


Figure 4: Analysis results (1.5 hour). Air flow rate at inlet50m^3/h (top), 60m^3/h (bottom)

Notes

Laundry dried by the drying system in a bathroom is well simulated. A larger flow rate of the air helps the laundry dry faster.

Melting and Condensation Analysis of Natural Ice

Melting/condensation analysis is tackled macroscopically using scSTREAM

Analysis Process using Temperature Recovery Method

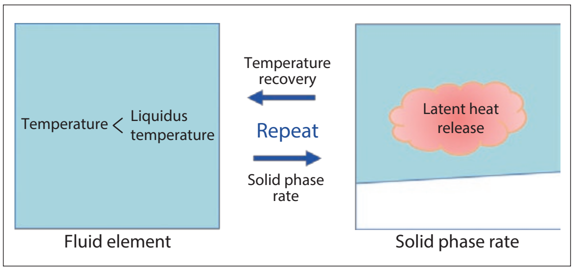


Figure 1: Temperature recovery method

- Define the volume fraction of solid in a fluid as solid phase rate.
- Assume equilibrium at solid-liquid interface and solve the change in solid phase rate by temperature recovery method.
- As shown in Figure 1, solve temperature of fluid element, and if temperature is below liquidus temperature (which matches solidus temperature for pure matter such as pure water), calculate solid phase rate from latent heat and specific heat.
- Next, recover temperature of fluid element by releasing (generating) latent heat equivalent to solid phase rate and by solving temperature of fluid element again.
- Repeat the above to find solid phase rate and temperature of fluid element.

Melting and Condensation Analysis of Natural Ice

Analysis Model

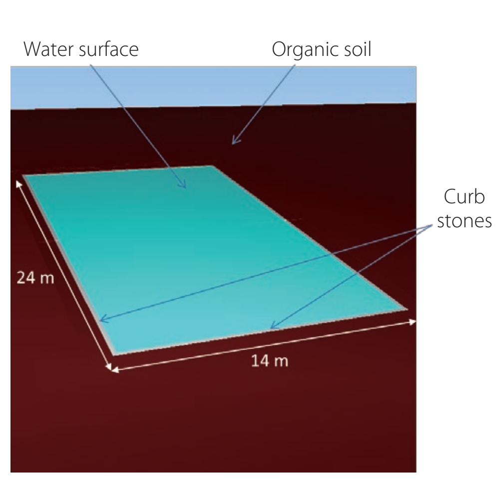
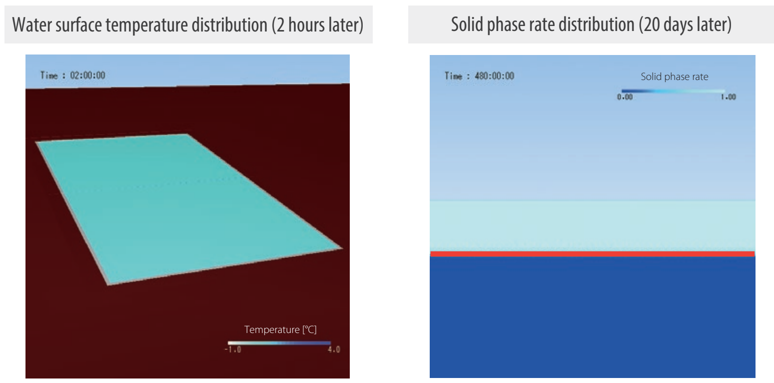


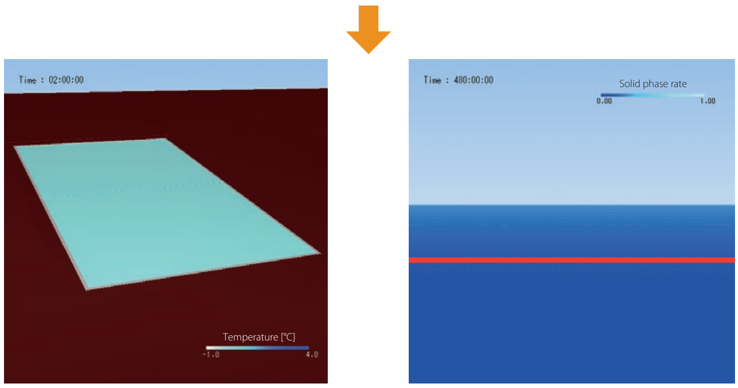
Figure 2: Water pond

Water pond	24 m long× 14 m wide× 0.5 m deep, surrounded by curb stones and organic soil
Top surface of pond	-8 ˚C Heat transfer coefficient 10 W/(m²K)
Bottom surface of pond	4 ˚C (heat conduction)
Analysis method	Transient analysis
Notes	Flow of water is not solved

Analysis Results



Fresh water: Growth of ice from water surface can be seen from the solid phase rate distribution



Sea water (salt water): Sea water is a compound liquid with 3.4 % salt (mass fraction), and water starts to freeze at -1.8 °C (liquidus temperature). The ice does not grow, and the drop of freezing point with salt is well simulated.

* Red line indicates 15 cm below the water surface

Figure 3: Analysis results showing fresh water (top) and sea water (bottom)

Notes

Figure 3 shows water surface temperature distribution after 2 hours and solid phase rate distribution after 20 days. From the result of fresh water, it can be seen that temperature drops almost uniformly at water surface, and ice grows from the surface. When fresh water is replaced with salt water such as sea water, ice does not grow, and the drop of freezing point with salt is well simulated.

scSTREAM

Water Flow Analysis of a Frozen Block

Thawing phenomenon by water flow is validated with melting/solidification analysis using scSTREAM

Modeling by Maximum Solid Packing Fraction

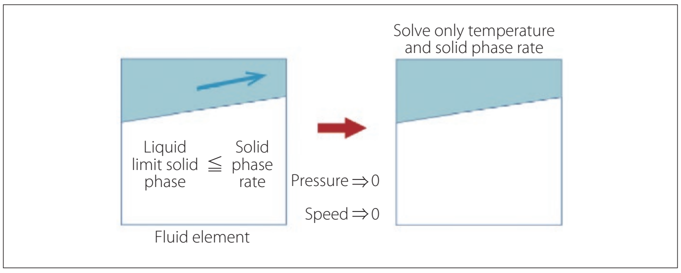


Figure 1: Modeling by maximum solid packing fraction

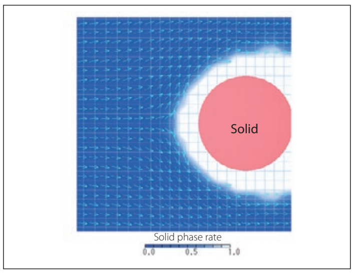


Figure 2: Velocity vector of a sample analysis

The flow of the liquid phase in solid-liquid coexistent state is affected by the volume fraction of the solid phase (solid phase rate). If the solid-fluid interface is smooth as in the case where ice is melted by water, modeling of a fluid element is possible by analyzing it only with the temperature and the solid phase rate, with the solid phase rate of the fluid element equal to or larger than the maximum solid packing fraction, and the pressure and the speed equal to 0.

Figure 2 shows velocity vector for a sample analysis of thawing of ice around a solid by flowing water. The grids are shown to distinguish fluid elements, and vectors of uniform length are shown for each of the elements.

Analysis of a Frozen Block

Analysis Model

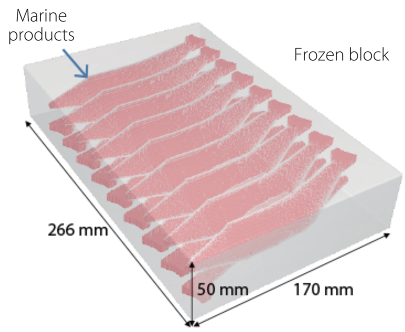


Figure 3: Frozen block

Marine products	Marine products 18 pieces (9 pieces/row), 266 mm long, 170 mm wide, 50 mm high
Material property	Density 900 kg/m^3, specific heat 2,000 J/(kgK), thermal conductivity 1.40W/(m·K)
Temperature	-20 ˚C (initial temperature of the frozen block) 4 ˚C (flowing water)
Simulation time	20 minutes
Analysis	Transient analysis
Maximum solid packing fraction	0.9

Analysis Results

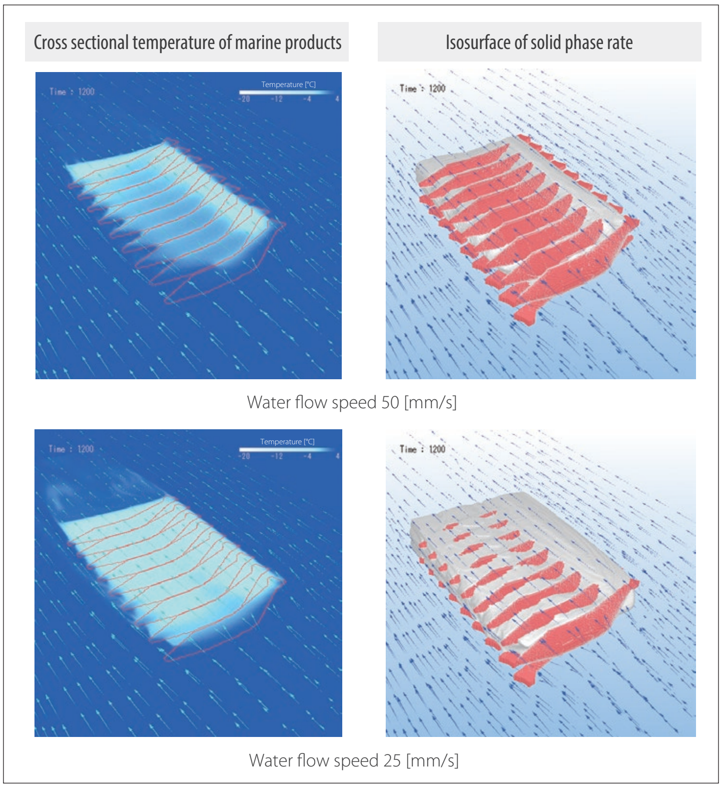


Figure 4: Analysis results
Cross sectional temperature and isosurface of solid phase rate (20 minutes later)
Water flow speed 50 [mm/s] (top) and 25 [mm/s] (bottom)

Notes

From the cross sectional temperature, all but one piece in front are below 0 ˚C, and it can be estimated that most of marine products are half-thawed. They can be drawn out of the flowing water at this point for natural thawing, which will allow for thawing in a short time without water dripping.

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