Computer Simulation of Ice Cream Solidification

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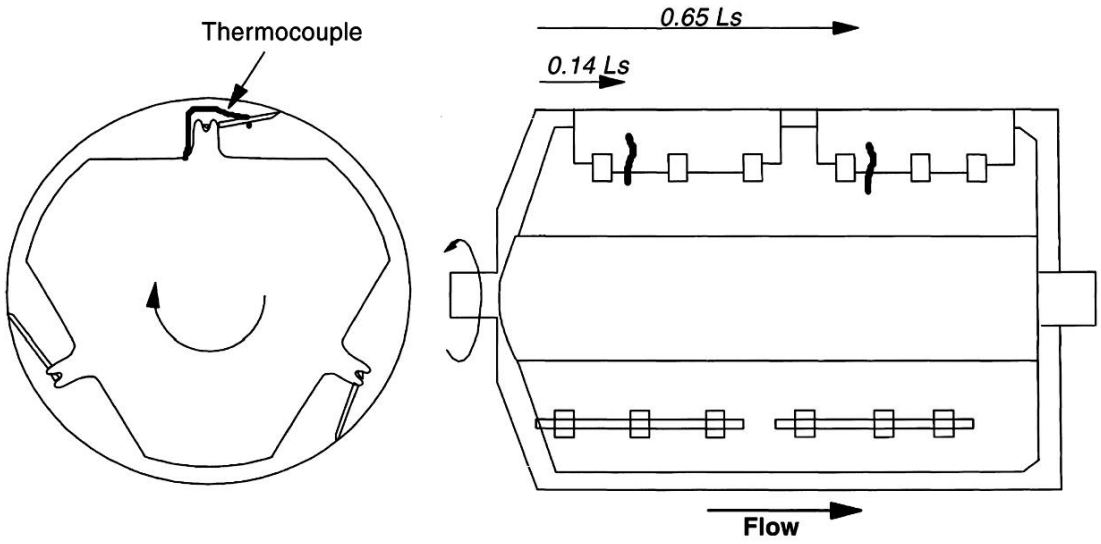
SUMMARY

- Ice Cream manufacturing
- Initial microstructure generation
- Microstructure discretisation
- Model scheme
- Surface determination
- Phase diagram
- Sugar diffusion
- Simulated microstructures

ICE CREAM MANUFACTURING

- Ice Creams manufacturing scheme

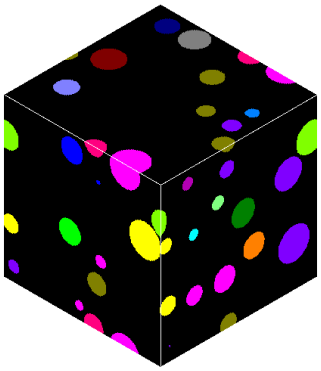


- Extrusion temperature is –3.5ºC.
- Exit volume fraction of ice seeds is 0.16
- Sugar concentration on the matrix is 0.05.
- Mean size of ice seeds is 33 μm.

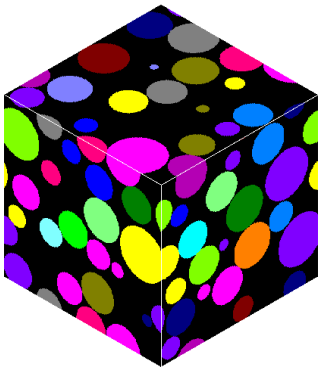
INITIAL MICROSTRUCTURE GENERATION

- 3D periodic microstructures were generated.
- Spherical ice seeds were located on the volume until a 0.16 volume fraction was reached.
- Log-normal size distribution of ice seeds.
- Different dihedral angles between seeds were allowed during location.

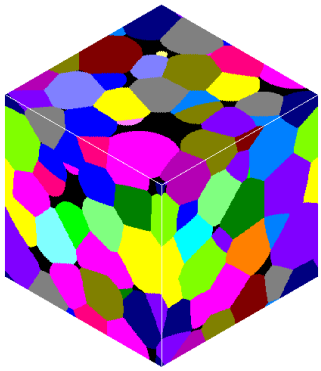
Dihedral Angle 0º
No contact allowed



Dihedral Angle 20º
Limited overlapping allowed

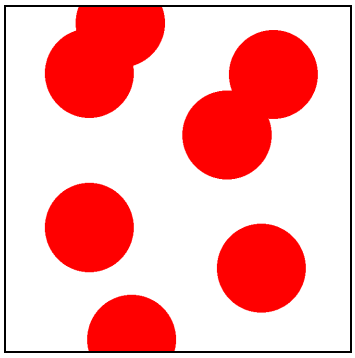


Dihedral Angle 180º
Free position

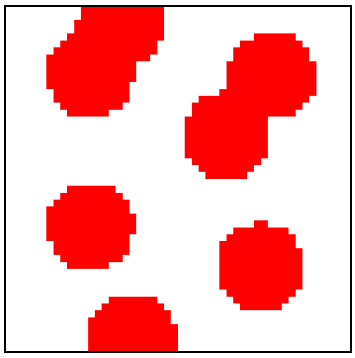


MICROSTRUCTURE DISCRETISATION

- Generated microstructures were discretised into cubic elements (voxels).



Analytic microstructure

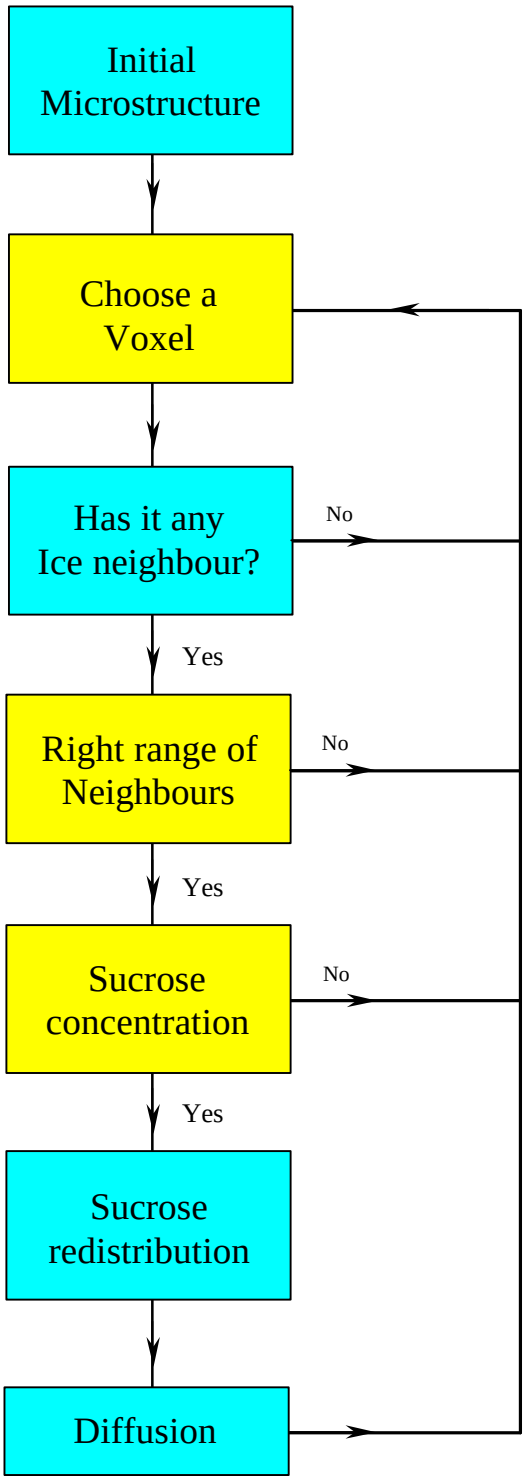


Voxelised microstructure

- Main advantages of voxels:
    - Identical shapes.
    - Regular spacing, i.e., the centre of a voxel will define it.
    - Fast and memory efficient for computing.

- Microstructures were discretised in $200 \times 200 \times 200$ voxels, i.e., 8 million elements.

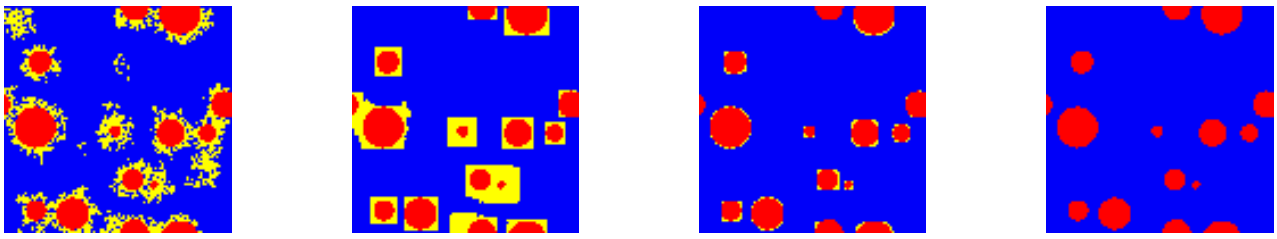
MODEL SCHEME



SURFACE DETERMINATION (1/4)

- Matrix voxels only can be solidified on ice seeds surface.

- Some simulations were performed with these steps:
    - Voxels are chosen at random.
    - If a chosen voxel has more than a preset face neighbours it is solidified.

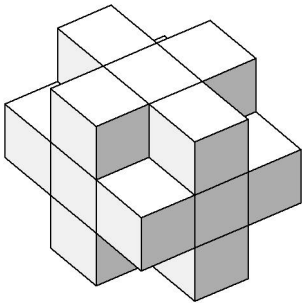


N≥1 N≥2 N≥3 N≥4

- Obtained microstructures are not realistic.

SURFACE DETERMINATION (2/4)

- Edge neighbours were considered to improve the model.



- Face and edge neighbours have “weights” according to their distance to the central voxel.

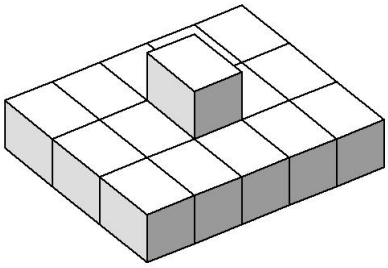
6 face neighbours	*	1	= 6
12 edge neighbours	*	0.7071	= 8.4852
Maximum number of neighbours			= 14.4852

- Voxels solidify according to a probability distribution.

SURFACE DETERMINATION (3/4)

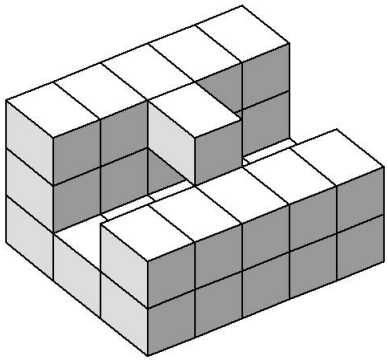
- Key configurations were studied to generate the distribution.

SURFACE GROWTH



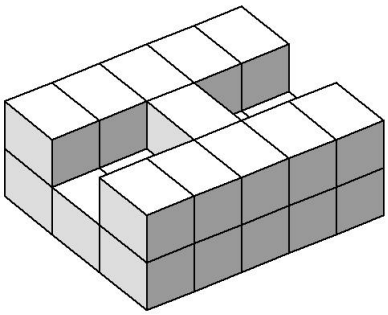
Number of neighbours
3.8284

HOLE GENERATION



Number of neighbours
3.8284

FILLING CHANELS



Number of neighbours
8.6568

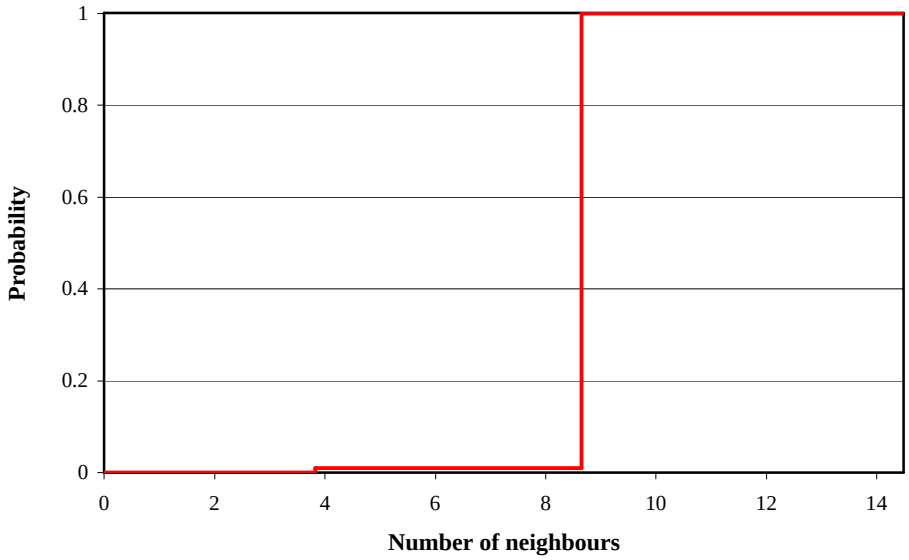
- If a voxel has less than 3.8284 neighbours it will never solidify (P=0).

- If a voxel has more than 8.6568 neighbours it will solidify (P=1).

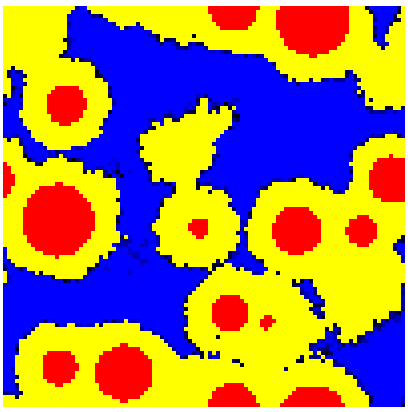
- If a voxel has more than 3.8284 and less than 8.6568 its solidification probability is 0.01.

SURFACE DETERMINATION (4/4)

- Final used distribution is:



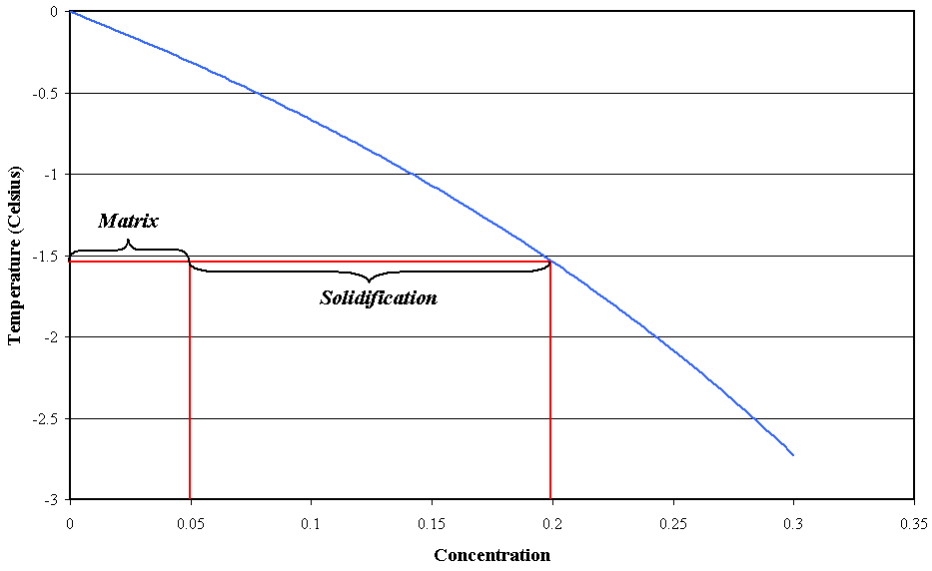
- Microstructures simulated using this distribution result in smooth surfaces and isotropic growths.



PHASE DIAGRAM

- The model takes into account the sugar concentration of each voxel.

- Each voxel on the surface has a solidifying probability proportional to its sugar concentration, according to the phase diagram.



- If a voxel solidifies, it moves all its sugar away to its face neighbours.

- This results in a layer of high sugar concentration surrounding ice particles.

SUGAR DIFFUSION (1/2)

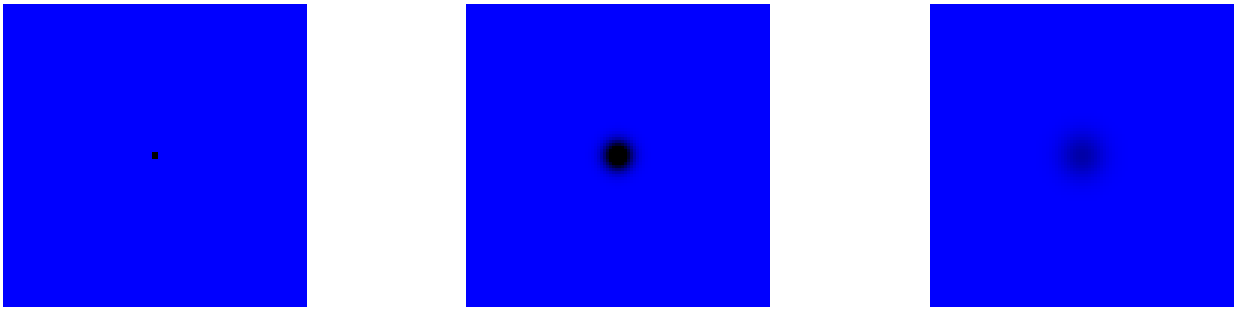
- To avoid such high concentration layers the model includes a diffusion algorithm.

- A finite differences approatch to the Fick's law was used.

$$c_{i,j,k}^{n+1} = c_{i,j,k}^{n} + D\frac{\Delta t}{\Delta x^2}\left(c_{i+1,j,k}^{n} + c_{i-1,j,k}^{n} + c_{i,j+1,k}^{n} + c_{i,j-1,k}^{n} + c_{i,j,k+1}^{n} + c_{i,j,k-1}^{n} - 6c_{i,j,k}^{n}\right)$$

- This algorithm gives isotropic movements of sugar.

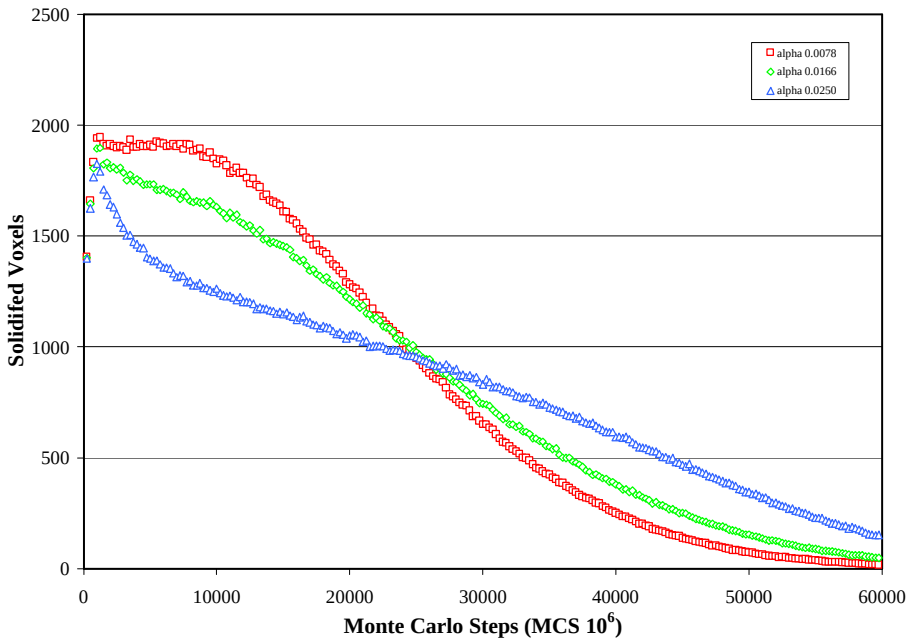
Initial Stage | **300 diffusion steps** | **800 diffusion steps**



SUGAR DIFFUSION (2/2)

- Diffusion algorithm needs much computation time.

- A diffusion step was applied after every 10^7 Monte Carlo Steps.

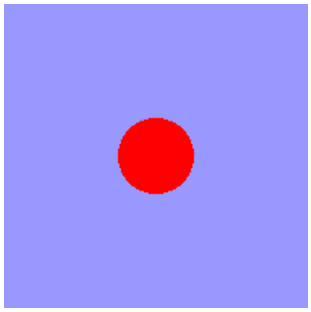


- Between two diffusion steps the solidification never attains 0.1% of the microstructure.

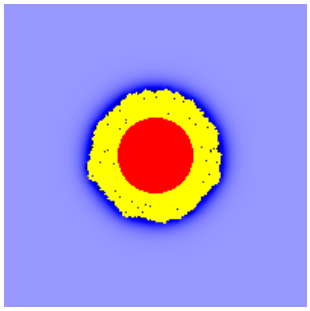
SIMULATED MICROSTRUCTURES (1/3)

- Evolution of a spherical seed.

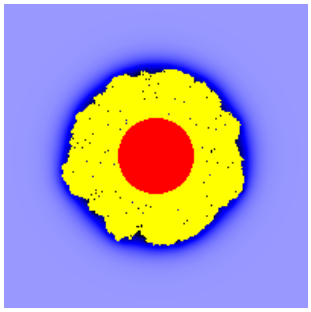
0 MCS



$3 \cdot 10^9$ MCS



$6 \cdot 10^9$ MCS

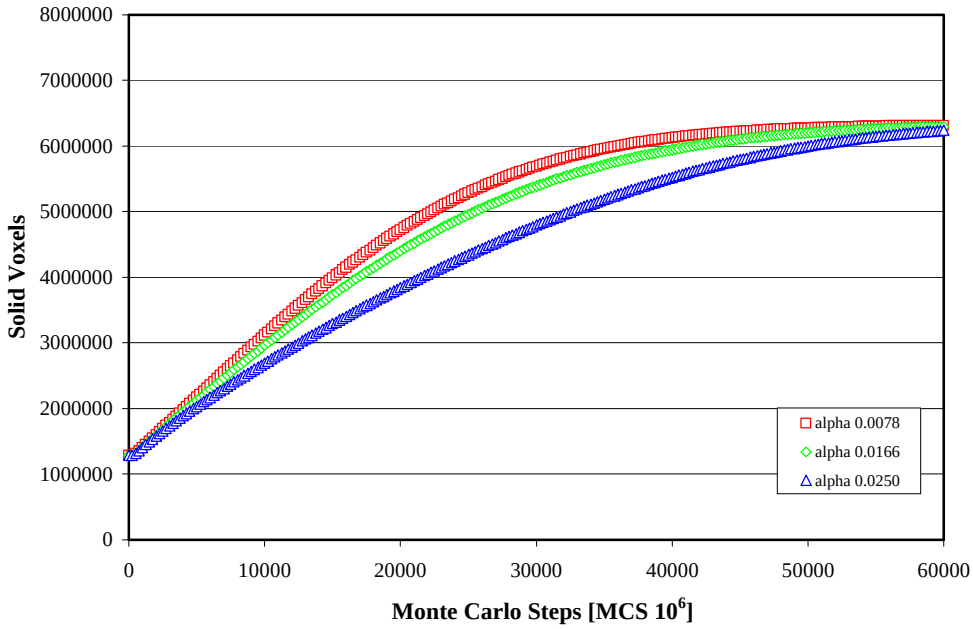


SIMULATED MICROSTRUCTURES (2/3)

- Final volume fraction of matrix can be calculated with…

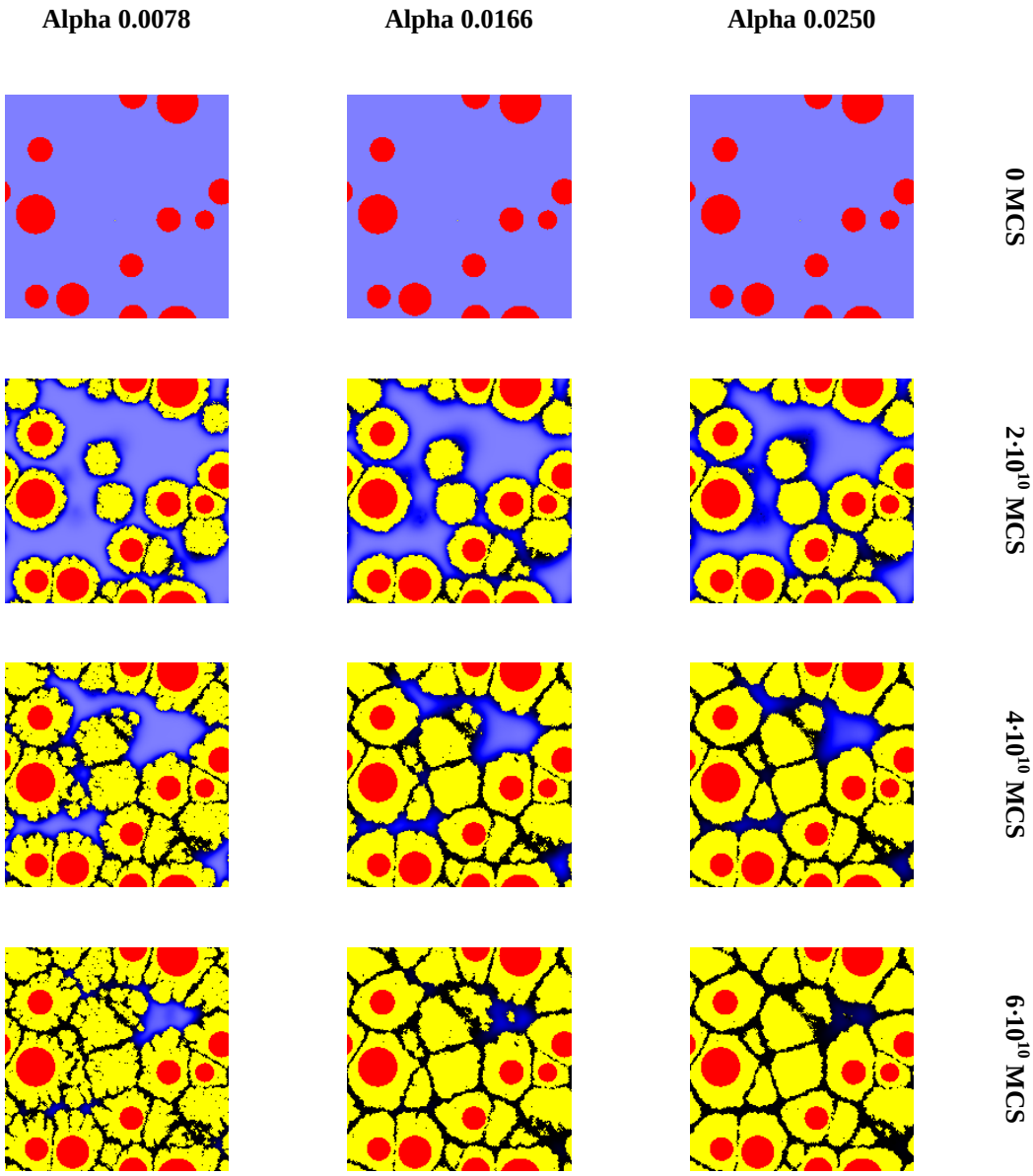
$$1 - \frac{C_{initial\ matrix} \times Vf_{initial\ matrix}}{C_{liquidus}} = Vf_{Max}$$

- Simulations using different diffusion rates reach the theoretical ice volume fraction (0.79).



SIMULATED MICROSTRUCTURES (3/3)

Ice-Cream microstructures simulated using different conditions.



REAL MICROSTRUCTURES