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Numerical Simulation of Compositional Redistribution Driven by isotopologue Fractionation During Solidification of D-T Fuel in ICF Targets

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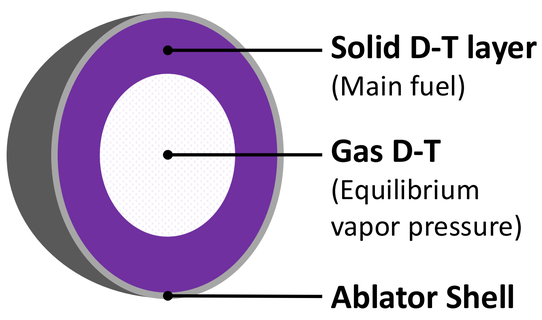
ABSTRACT

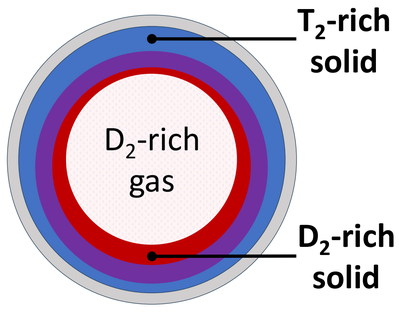
- In ICF, compositional homogeneity of cryogenic D–T fuel targets is critical for fusion performance.
- Isotopologue fractionation induces a radial concentration gradient within the solid D-T layer and alters the equilibrium composition of the central D-T gas.
- A comprehensive numerical framework was developed to simulate the compositional distribution in D-T mixture during solidification.
- The detrimental effects of composition inhomogeneity on fusion efficiency were examined.

BACKGROUND

Cryogenic D-T target for ICF



Fractionation

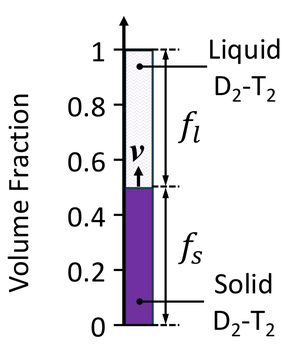


(D-T： deuterium–tritium mixture)

Numerical simulation method was developed to quantify the compositional distribution in D-T target during solidification

SIMULATION 1: Compositional distribution during unidirectional solidification

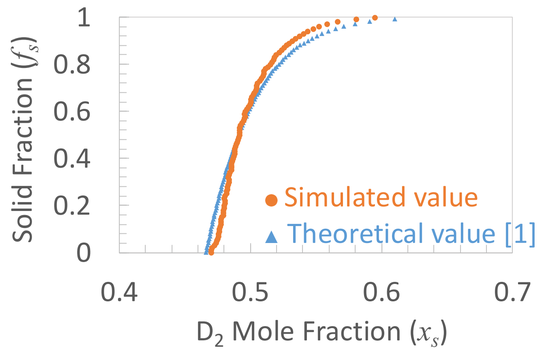
Unidirectional Solidification



(D$_2$-T$_2$ mixture)

Mesh

Simulated versus theoretical

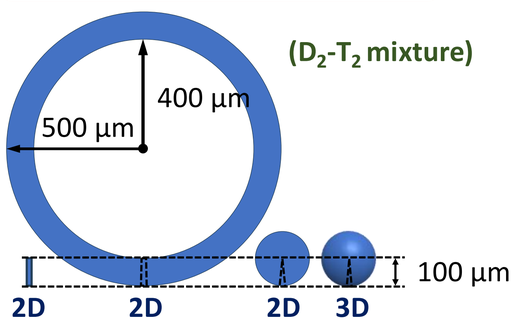


Maximum fractionation [2]

Simulation results show good agreement with the theoretical values confirming the validity of the numerical model

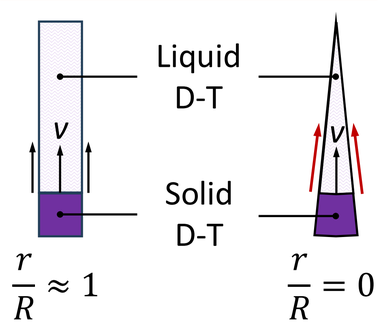
SIMULATION 2: Compositional distribution during radial solidification

Models with different r/R



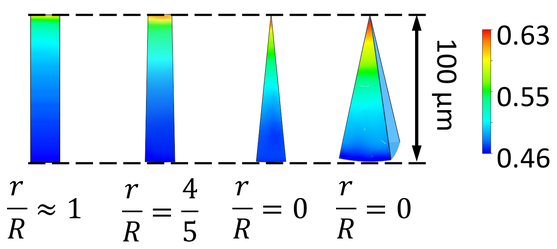
Mesh

Solidification Direction

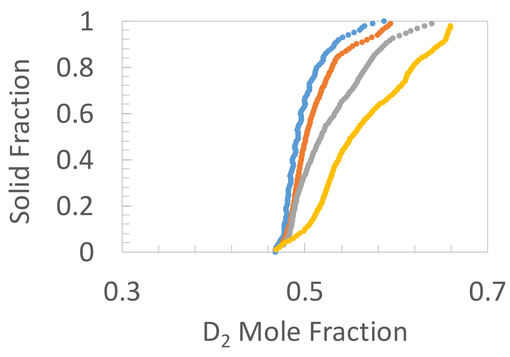


Parallel Radial

D$_2$ mole fraction distribution



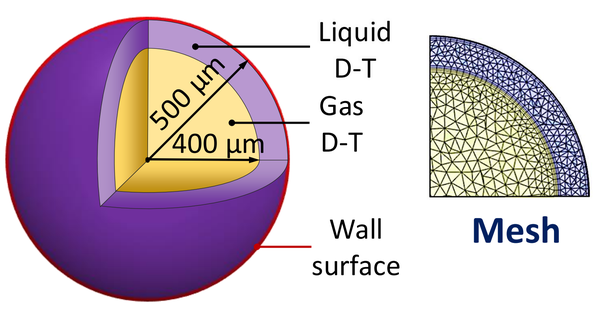
Radial distribution



Relatively high r/R is recommended in target design

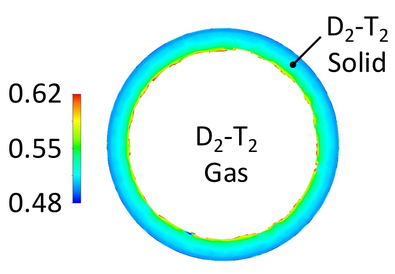
SIMULATION 3: Compositional distribution in D-T target

3D model of the D-T target



Ignoring Gravity

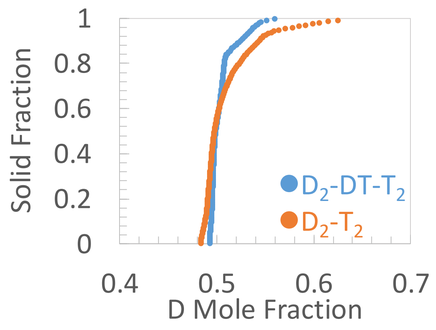
D$_2$ mole fraction distribution



D$_2$:T$_2$ = 1:1

Ignoring Beta-decay

Radial distribution



Empirical Formulas for P_i^S (Pa) vs. T (K) [2]

Raoult's law: $P_i^G = P_i^S X_i^S$

$$X_i^G = \frac{P_i^G}{\sum_i P_i^G}$$

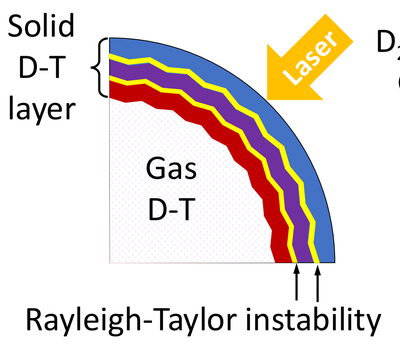
P_i^S : Equilibrium vapor pressure of the pure component i
P_i^G : Partial pressure of the component i
X_i^G : Mole fraction of the component i

	D$_2$:T$_2$ = 1:1	D$_2$:DT:T$_2$ = 3:4:3 [2]
Radial distribution of D atom content in solid	0.480 ~ 0.600	0.493 ~ 0.571
D atom content in gas	75.6%	67.9%

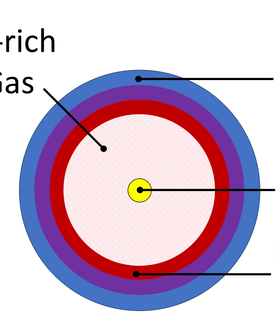
D$_2$ distribution in the solid layer exhibits a radial mole fraction gradient
D atom content in the gas phase is significantly in excess

DISCUSSION

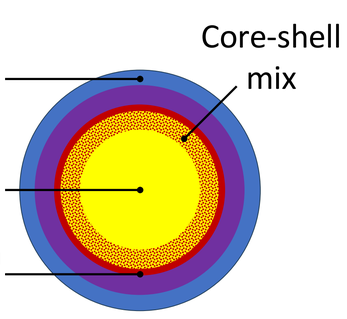
Compression Phase



Ignition Phase



Burn Phase



Rayleigh-Taylor instability:

1) Radial density gradient
2) Irregularities along isodensity surfaces

D-T reaction: $D + T \rightarrow {}^4He + n$

Optimal Ratio: D : T = 1 : 1
T$_2$-rich areas: D : T < 1 : 1
D$_2$-rich areas: D : T > 1 : 1

Rayleigh-Taylor instability can threat to implosion uniformity

D- or T- enriched areas may reduce fusion reaction efficiency

CONCLUSION

- Simulation results agree well with the theoretical values, confirming the validity of the numerical model
- Relatively high r/R is recommended in target design
- D atom distribution in the solid exhibits a radial mole fraction gradient; D atom content in the gas phase is significantly in excess
- Inhomogeneity in target may affect the ICF performance in multiple stages

These findings offers guidance for predicting and improving compositional homogeneity in target design

ACKNOWLEDGEMENTS

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