New insights on fouling mechanisms explored by rheo-fluidics at the microscale

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The fouling process in dairy industry

What is fouling?

Accumulation of solid components
of the dairy solutions
on stainless-steel surface

FLOW CHARACTERISTICS

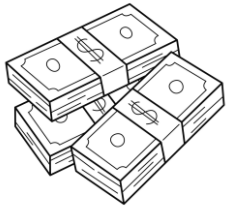
THERMAL GRADIENTS

Where do we observe fouling?

Membranes, filters
(filtration process)

Evaporators, heat exchangers
(pasteurization, sterilization)

DIFFERENT SCALE
AND PHYSICO-CHEMICAL DYNAMICS



Daily cleaning sessions

Which are the consequences?

- Significant pressure drop
- Lowered thermal exchange
- Pipe blockage

Visser J and Jeurnink Th J M (1997). Experimental Thermal and Fluid Science.

The emerging question of the evaporators

Concentration of dairy fluids before spray drying (energy saving)

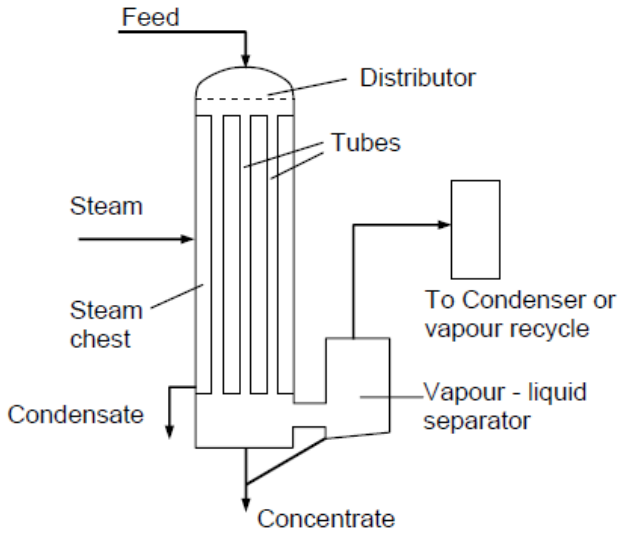
Spraying Systems Co.®

Production of "commodities"

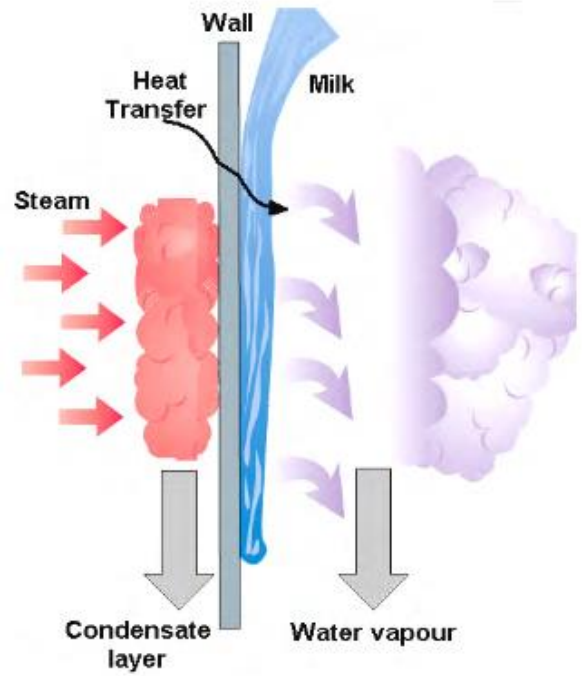
Wide range of processed fluids

Infant Milk Formulas (IMFs)

FALLING FILM SETUP



Broome S., 2005.



Main characteristics

- Constant surface temperature (T = 45-80 °C)
- Increasing top-to-bottom concentration
- Double interface

State of the art on fouling mechanisms

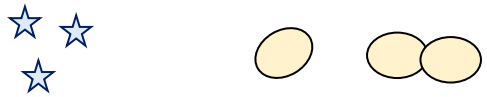
Bansal B and Chen X D (2006). Comprehensive Reviews in Food Science and Food Safety.
Visser J and Jeurnink Th J M (1997). Experimental Thermal and Fluid Science.

No direct observation!

1. Equipment like "black boxes"
2. Only global mass/energy balances
3. Offline analysis of the solid layers

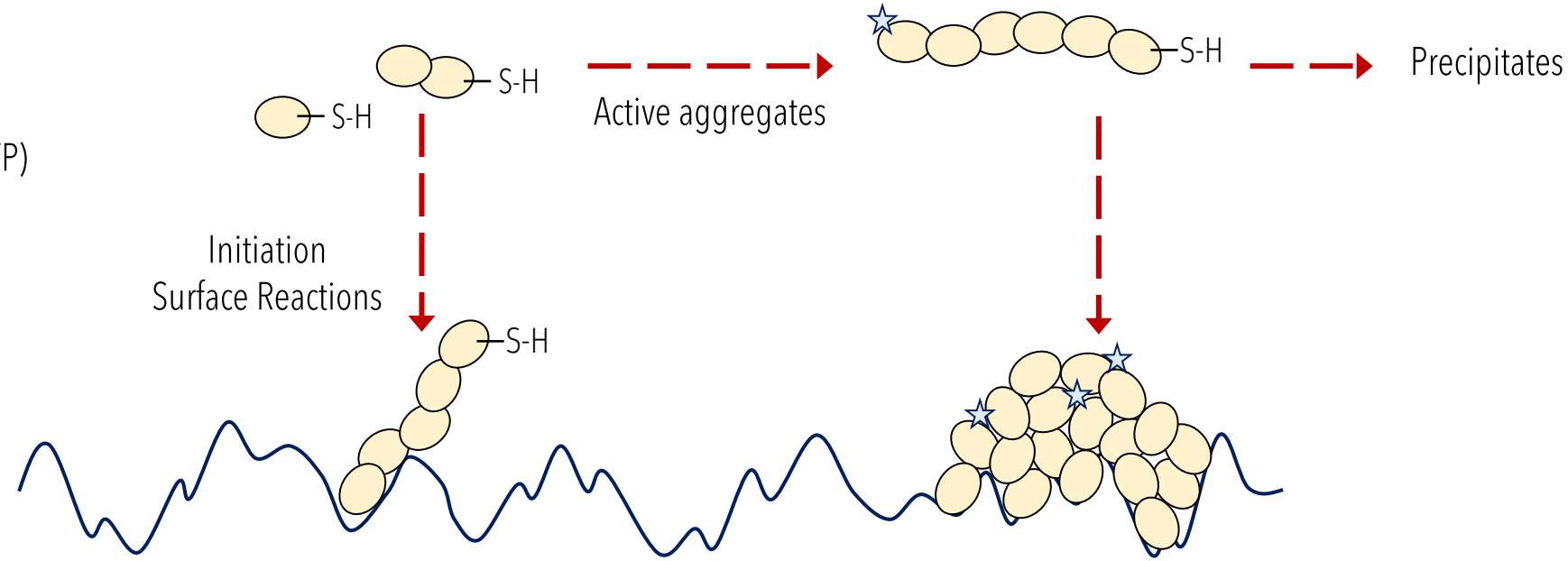
BULK SOLUTION
Milk, Protein Suspensions

Minerals (Ca^{2+}) Whey Proteins (WP)



T > 65°C

PROTEIN DENATURATION

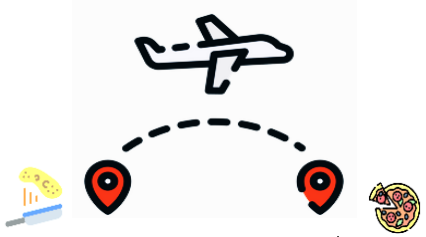


SURFACE PROPERTIES
Roughness, mechanical properties

Jimenez M, Delaplace G et al. (2013). Journal of Colloid and Interface Science

A microscopic journey: open questions

M. Grostete
Ph.D. Thesis
ENTEVAP Project (2022-25)



STLO Science & technologie du lait & de l'œuf

DICMaPI Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale Università degli Studi di Napoli Federico II

Prof. G. Tomaiuolo

INRAE

MINIATURIZATION OF THE DAIRY EQUIPMENT CONDITIONS

When?

Driving forces governing WP denaturation/accumulation

- Temperature
- protein concentration
- **shear rate**

Where?

Microscopic dynamics at the surface and in the bulk

Surficial deposit growth VS aggregate formation

How?

Nature of protein/surface interactions

- Chemical adsorption
- Short-range attractions

Deposit formation: an alternative scenario

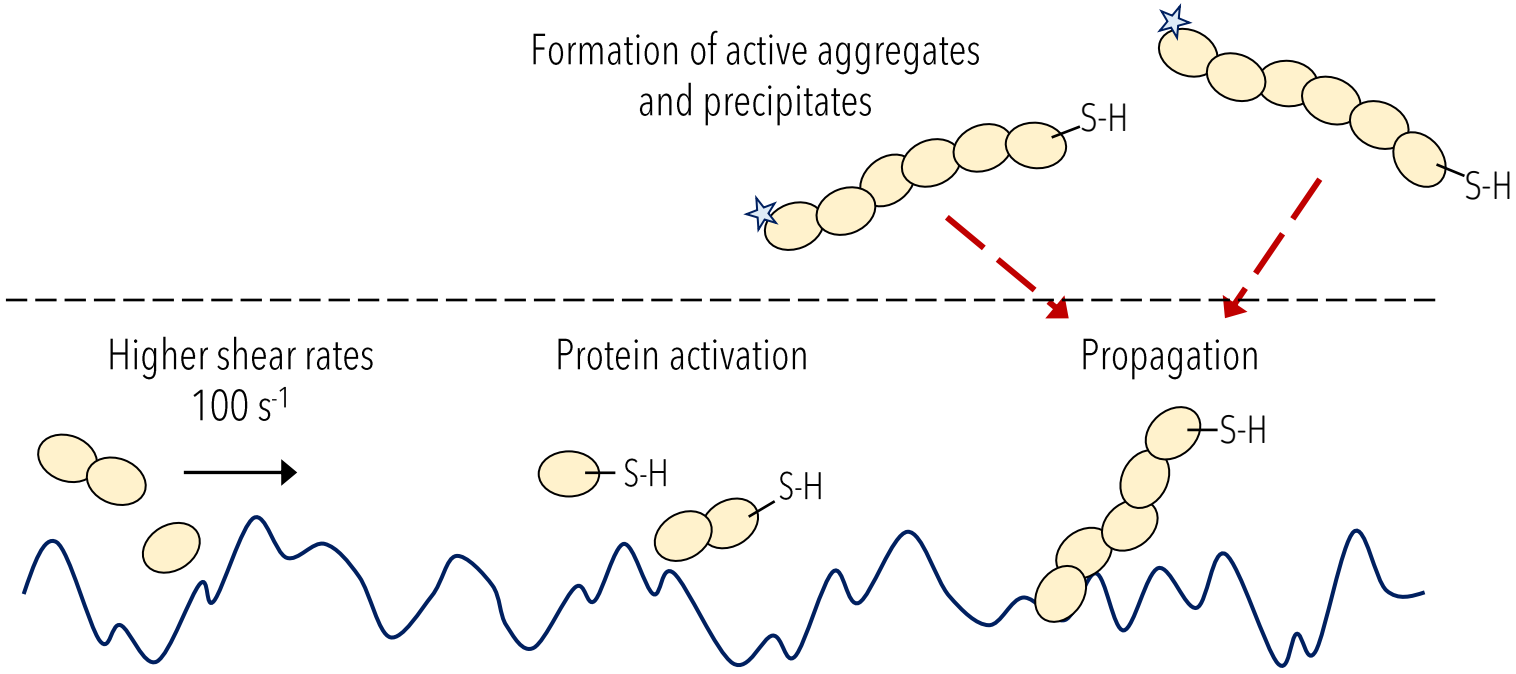
No fouling observed for T < 65°C

Jeurnink Th J M, Walstra P, de Kruif C G (1996). Netherlands Milk and Dairy Journal.

Absence of protein denaturation

→ Deposit development even at T=45°C in evaporators

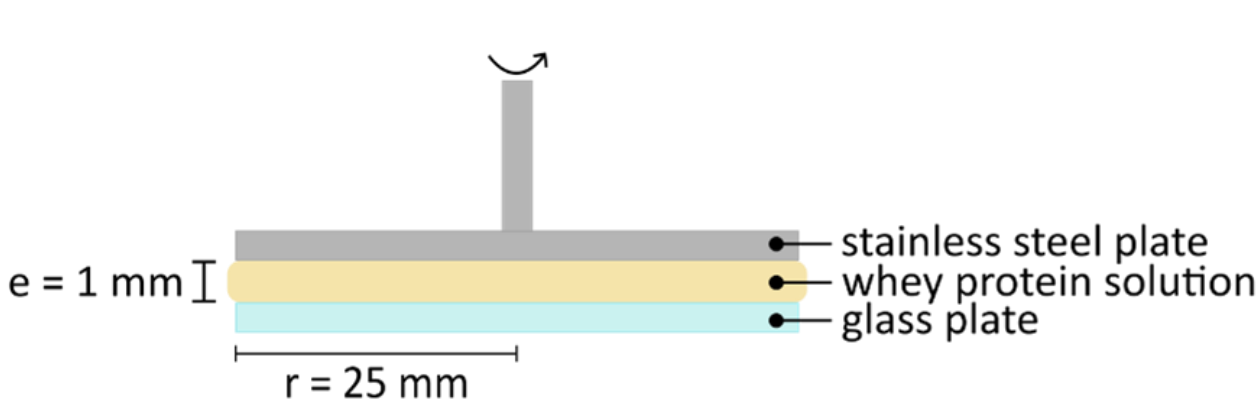
DOUBLE IMPACT OF TEMPERATURE AND SHEAR RATE

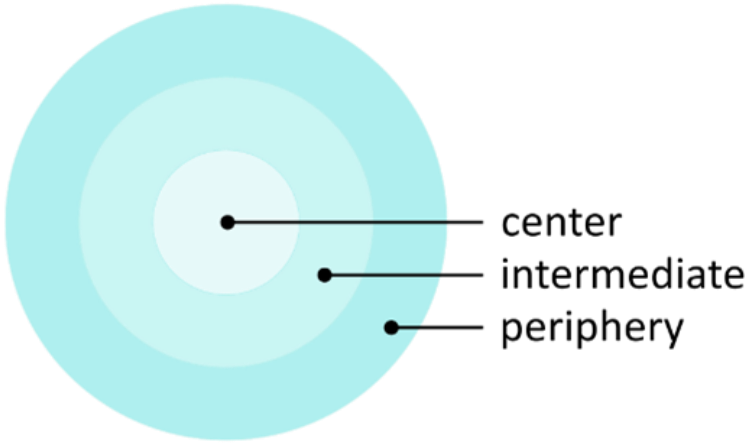


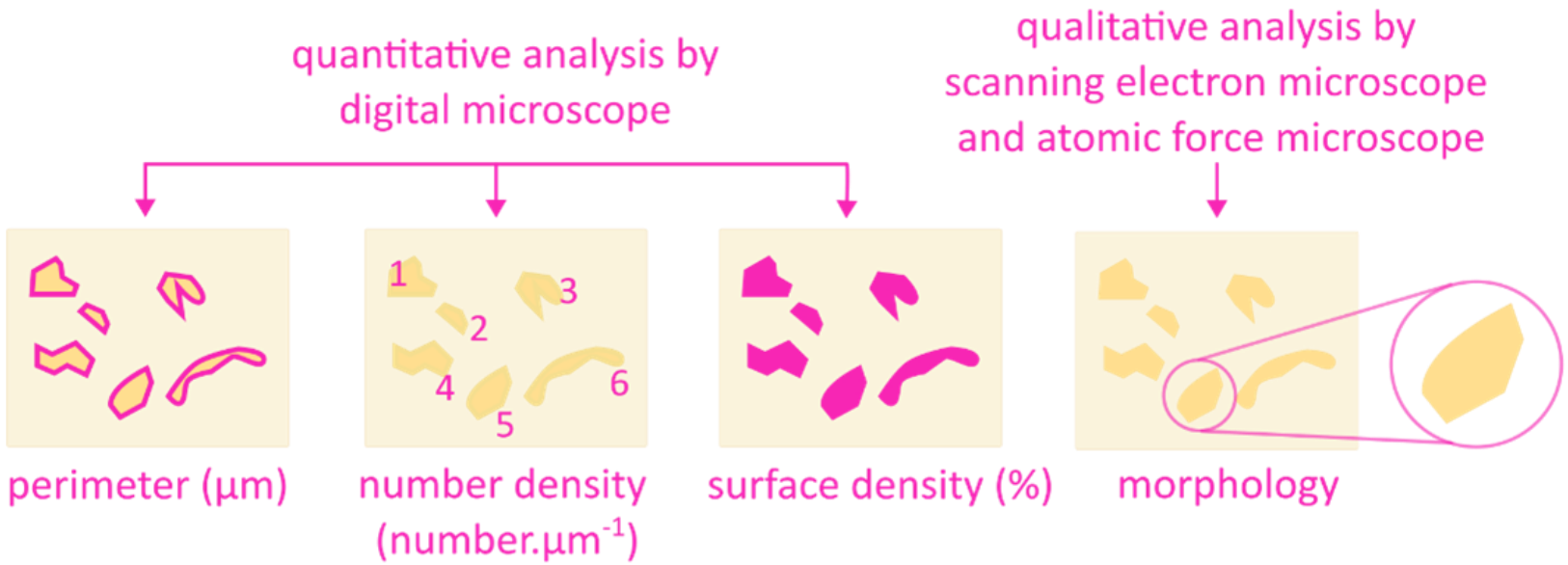
Passive fouling
PROPAGATION

Active fouling
INITIATION

Rheofluidics: a simple and flexible strategy

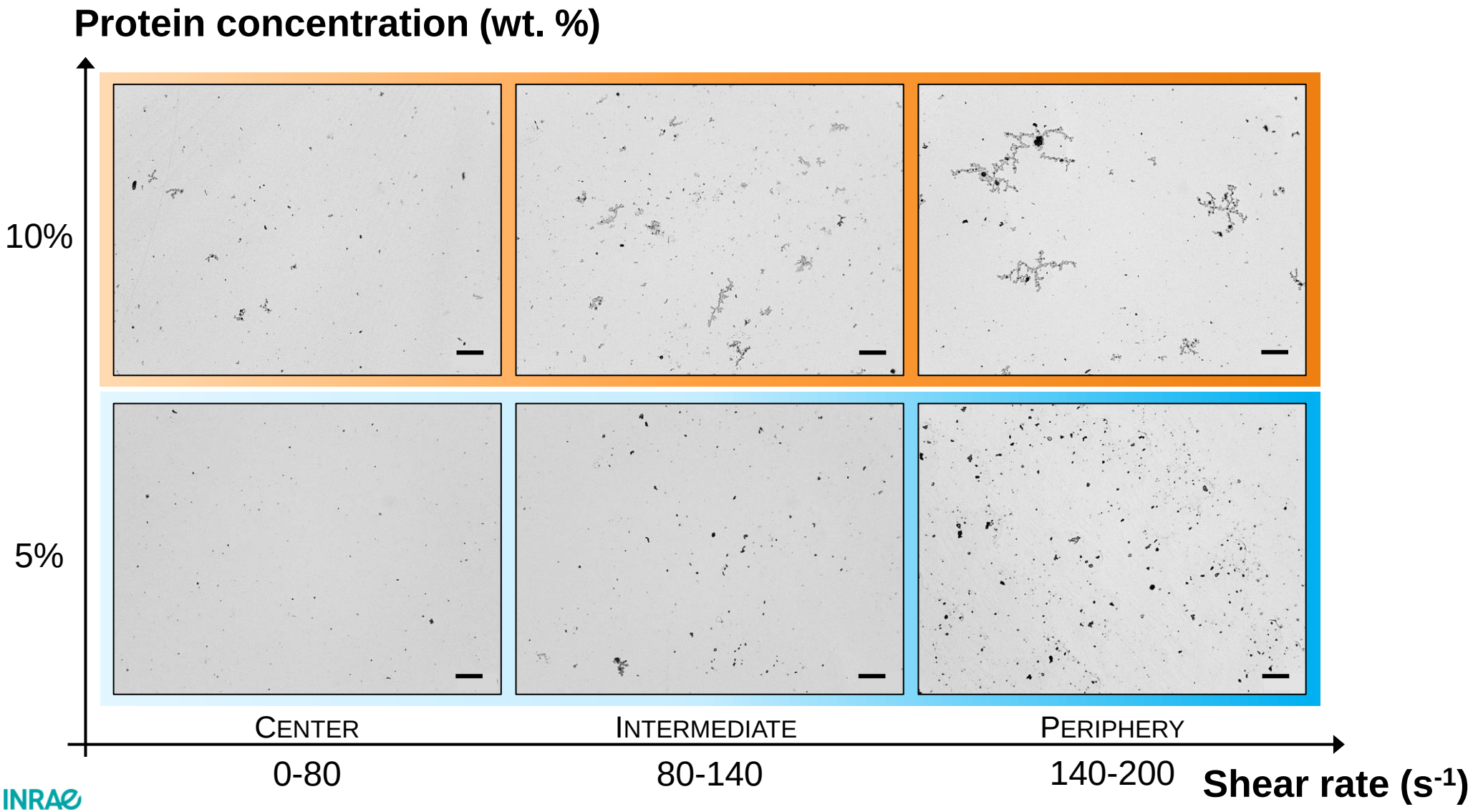






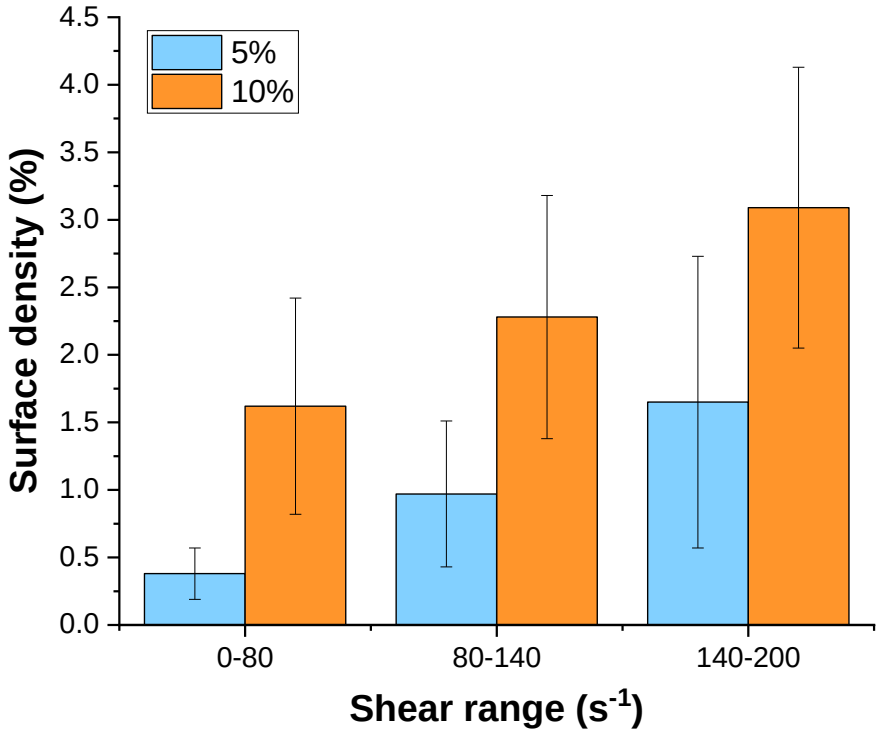
Grostete et al. (2024), Int J of Biological Macromolecules.

Qualitative observation of WP surficial deposits

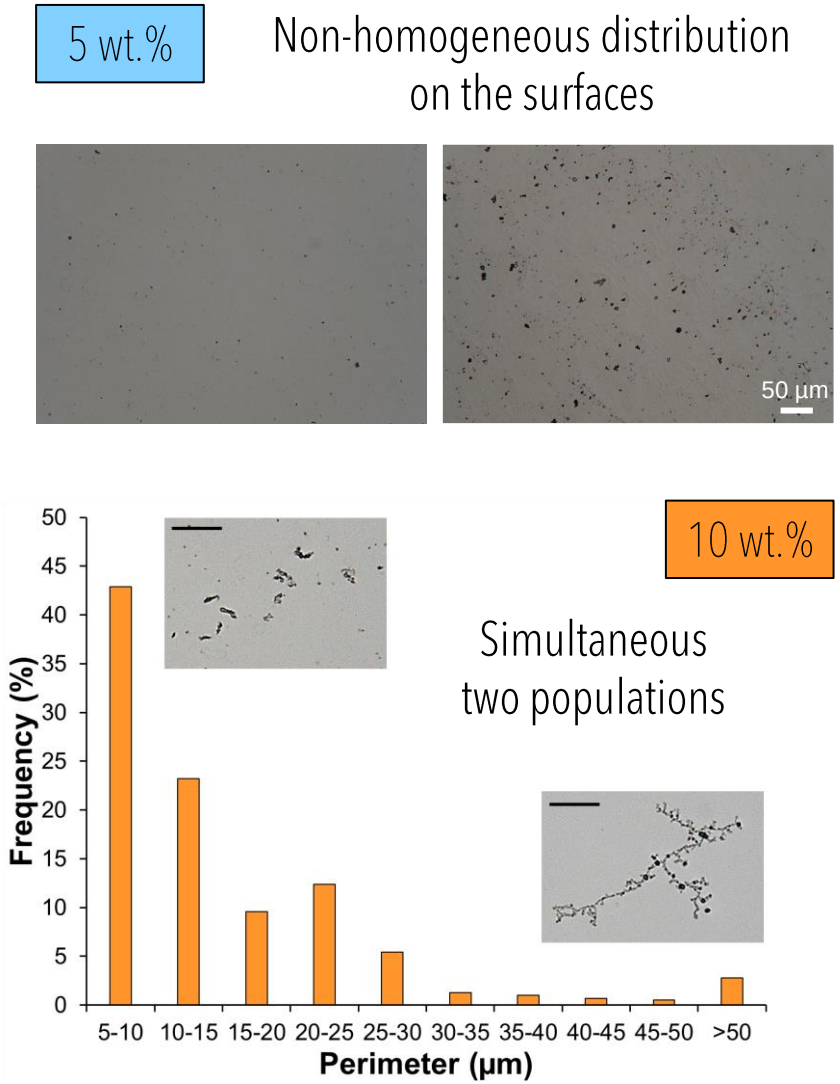


Grostete et al. (2024), Int J of Biological Macromolecules.

Quantification of the shear impact

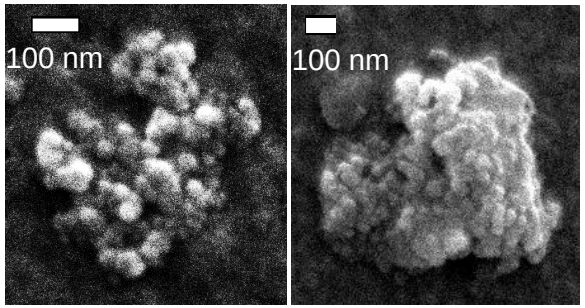


High standard deviations because of dynamics of protein accumulation

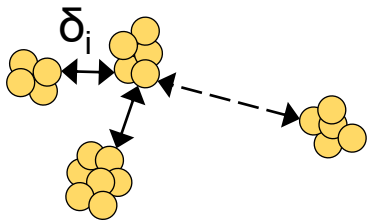


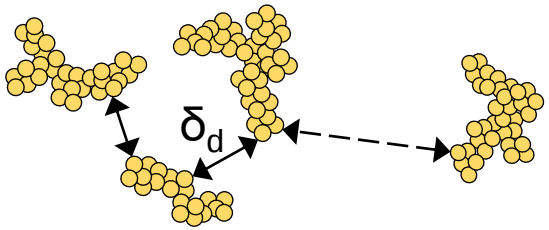
Grostete et al. (2024), Int J of Biological Macromolecules.

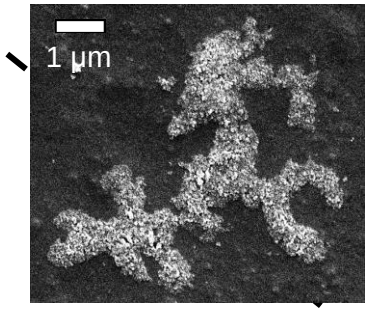
Hypothesis on the stages of protein accumulation



INITIATION POINTS







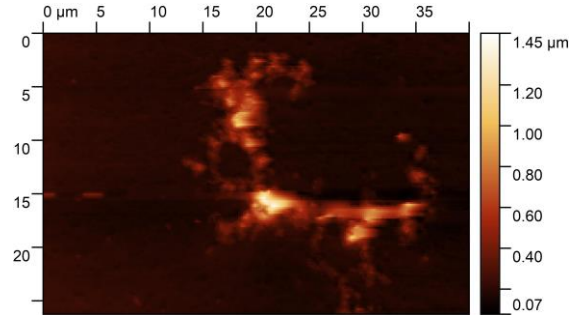
PRIMARY DEPOSITS

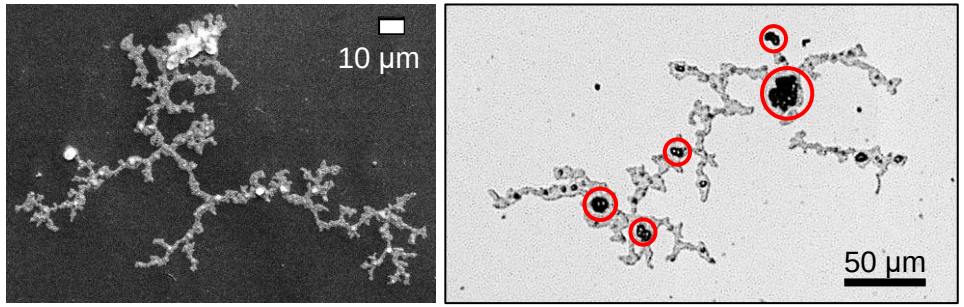
- Thermal denaturation and adsorption ✓
- Role of the shear stress ✗

TIME AND DISTANCE ARE CRUCIAL PARAMETERS

- Interconnection of primary deposits
- Structure complexification

PHYSICO-CHEMICAL NATURE OF THE DEPOSITS

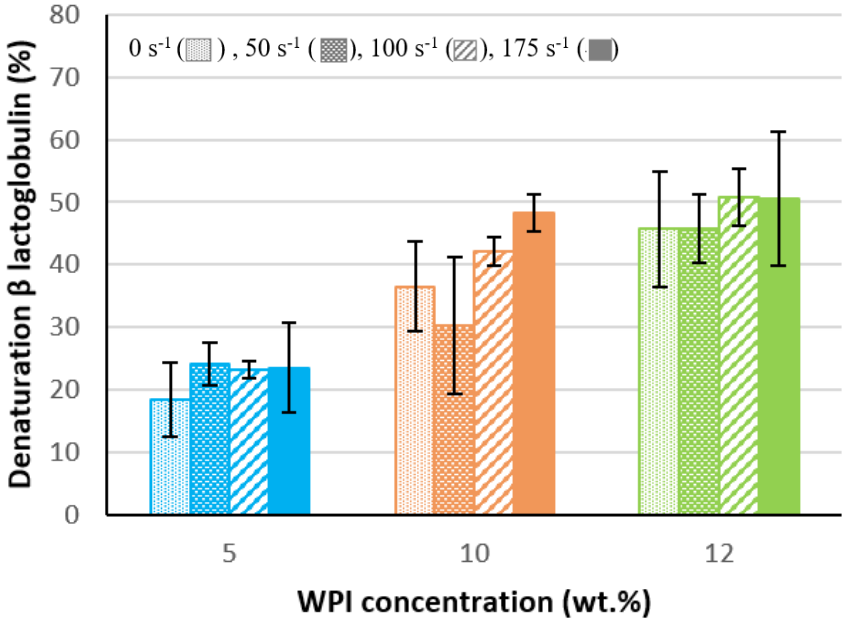




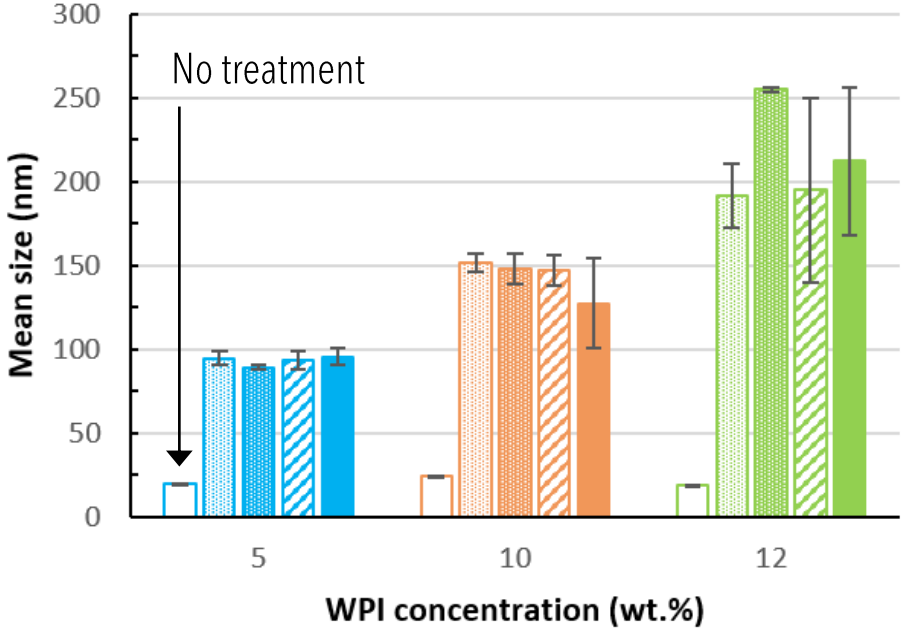
BRANCHED STRUCTURES

What happens in the “bulk”?

Tests by con-and-plate rheometers



Grostete et al., JCIS, close to submission.



Denaturation in the bulk governed by thermal effect and protein concentration

Impact on protein-protein interactions and WP aggregate formation

Submicronic WP aggregates predominant in the solutions (confirmed by microscopy observations)

ENHANCED DEPOSIT PROPAGATION

DOES IT EXCLUDE SHEAR-INDUCED DENATURATION?

Conclusions

Surface

- Increasing shear stresses enhance deposit formation in terms of number (dilute conditions) and shape complexification (concentrate conditions)
- Evident effect of the shear when combined with thermal one
- Deposit formation possibly due to both chemical and physical interactions next the surface

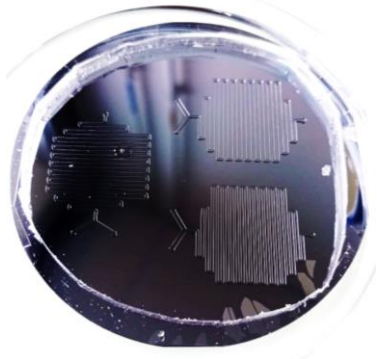
Bulk

- No impact of the shear on protein denaturation and aggregate mean size
- Combined effect of temperature and protein concentration

What's next?

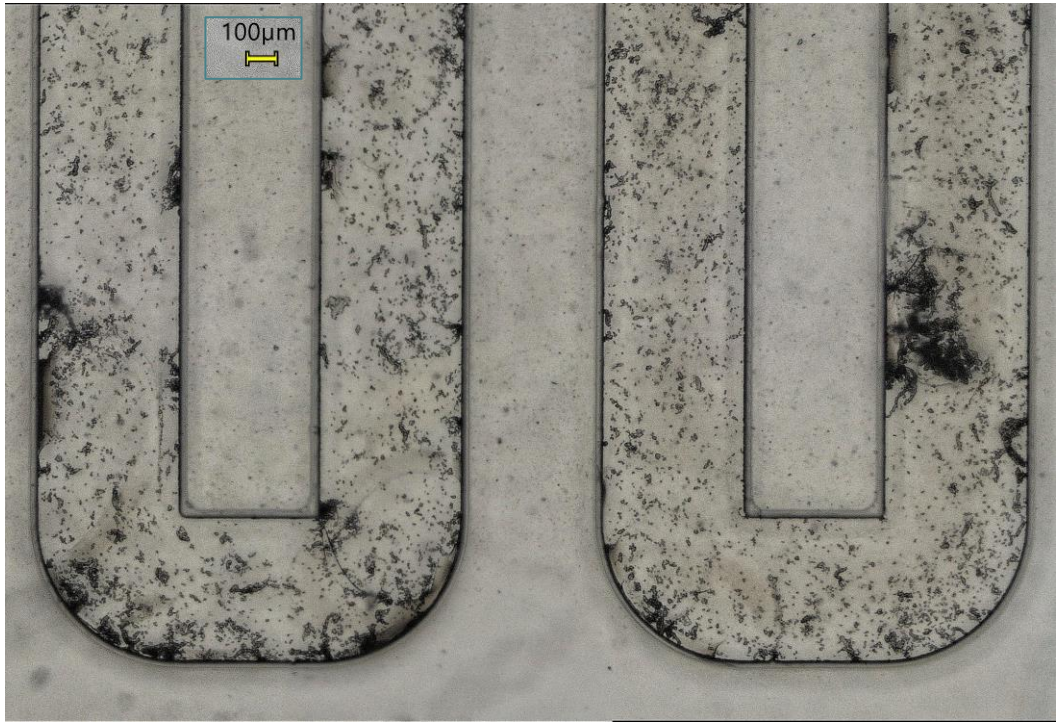
Direct observation of the phenomenon

Microfluidics



Preliminary results and exponential difficulties

Visit the poster of Margot

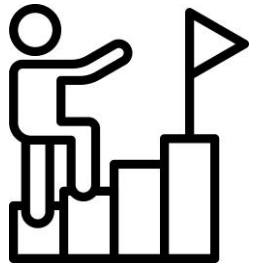


Experimental challenges

- *Repeatability* of the experiments (defects, bubble formation)
- *Control* of the temperature (device and solution)
- *Estimation* of the shear (rheometer vs wall shear)

DEEPENED INVESTIGATION LEADS TO MORE COMPLEX QUESTIONS

- Shear intensity and shearing time
- Absolute temperature and ΔT
- Air-liquid interfaces



Grazie a tutti per la vostra attenzione
Please, bring me back home!

mar	mer	gio	ven	sab	dom	lun	mar
19° 13°	17° 8°	17° 7°	17° 4°	18° 6°	19° 8°	20° 12°	21° 12°

Risultati per **Rennes, Francia**