Experimental and Simulations Related to Microcellular Injection Molding

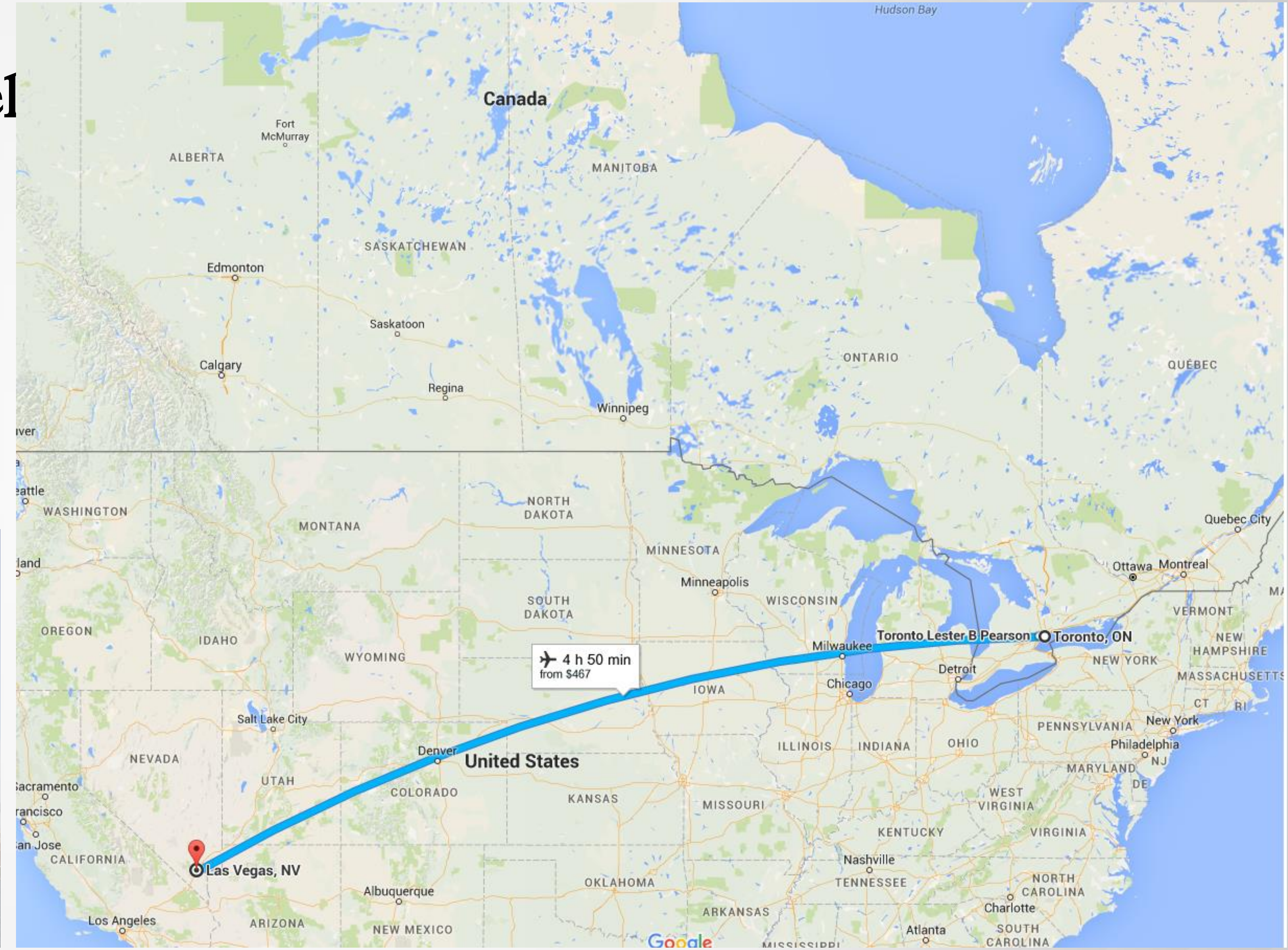
Vahid Shaayegan, University of Toronto

Dr. Sejin Han, Principal Research Engineer, Autodesk Moldflow

Dr. Franco Costa, Senior Research Leader, Autodesk Moldflow

Microcel

Vahid Shaayegan
v.shaayegan@mail.utoronto.ca



Vahid Shaayegan
v.shaayegan@mail.utoronto.ca

Microcellular Plastics Manufacturing Laboratory

Background:

BASc: Industrial Metallurgy & Manufacturing Engineering
MASc: Materials Science and Engineering

MASc: Physical and Rheological Properties of Polymers;
Rheology of Blends

PhD:
- Investigation of the Mechanism(s) of Cell Nucleation and Growth in Foam Injection Molding;
- Microcellular Foam Injection Molding;
- Functional Polymers.

Experimental and Simulations Related to Microcellular Injection Molding

Agenda:

- Visualization Equipment and Mold Design
- Mechanisms of Cell Nucleation and Growth in Low- and High-pressure Foam Injection Molding (FIM)
- Foam Injection Molding using Gas-Counter Pressure (FIM+GCP)
- Foam Injection Molding with High Expansion (FIM+MO)
- Application of Nucleating Agents (added or inherit)
- Simulation of Microcellular Injection Molding Process

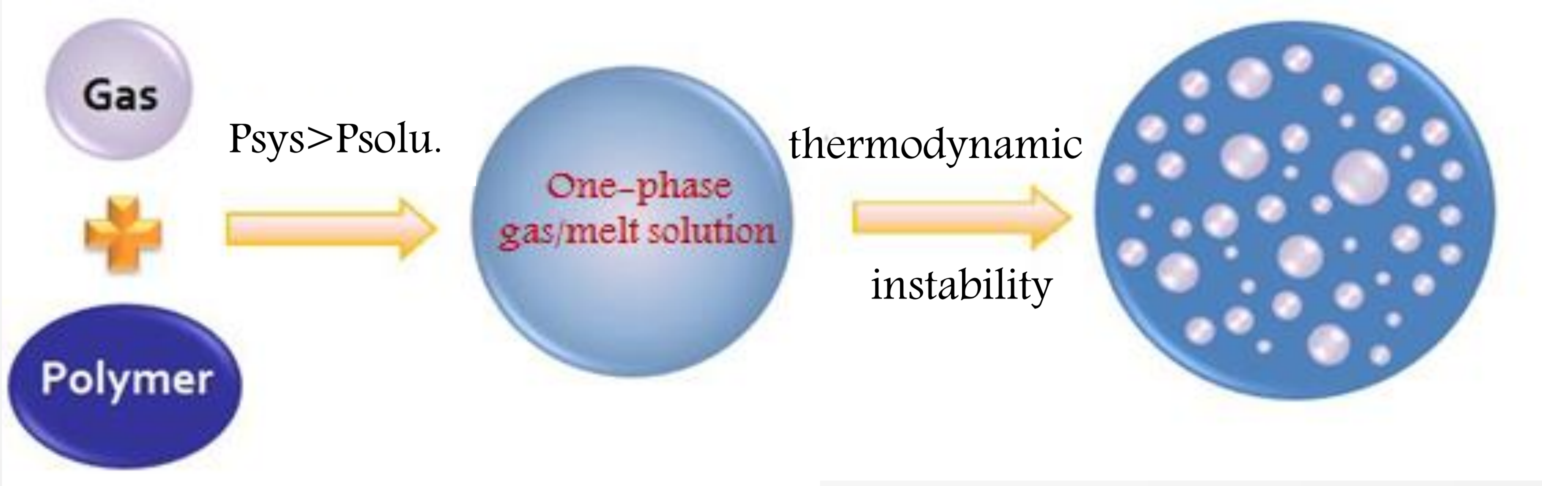
Introduction

Plastic Foams

1. Dissolution of a blowing agent (CO_2, N_2) in the polymer melt to make a one-phase, homogeneous melt/gas mixture;

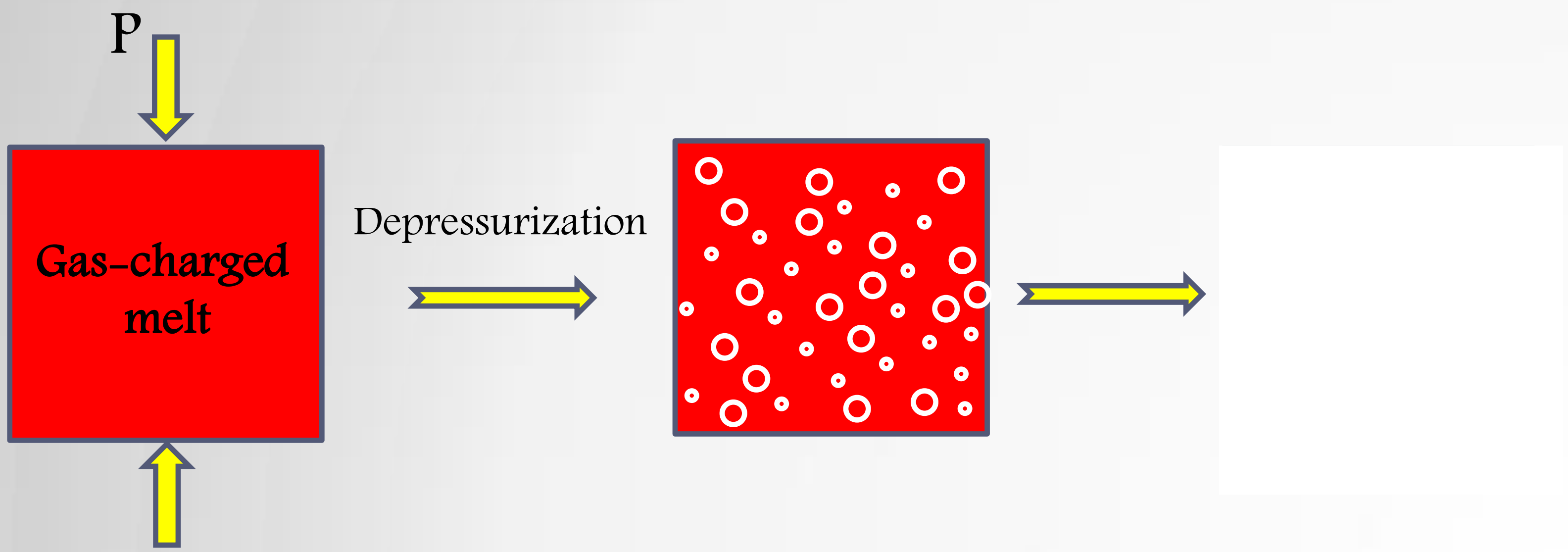
2. Cell nucleation *via* thermodynamic instability

3. Cell growth

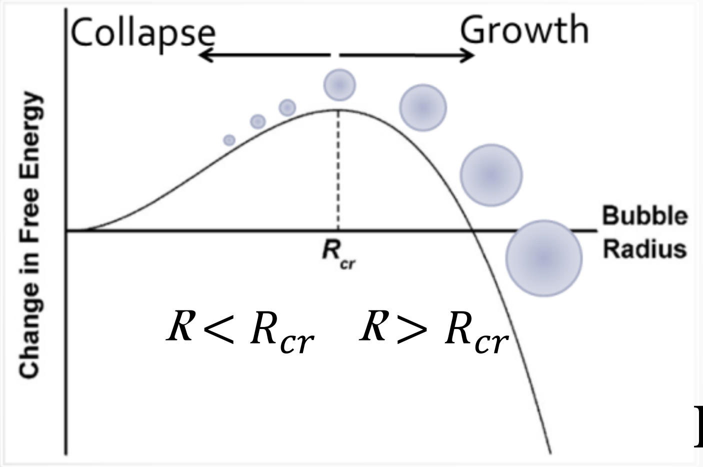


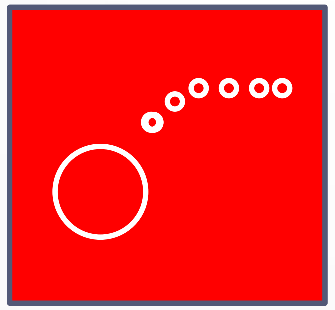
Nucleation and growth

Dissolution Nucleation Growth



- γ: interfacial tension
- P_{bub}
- P_{sys}

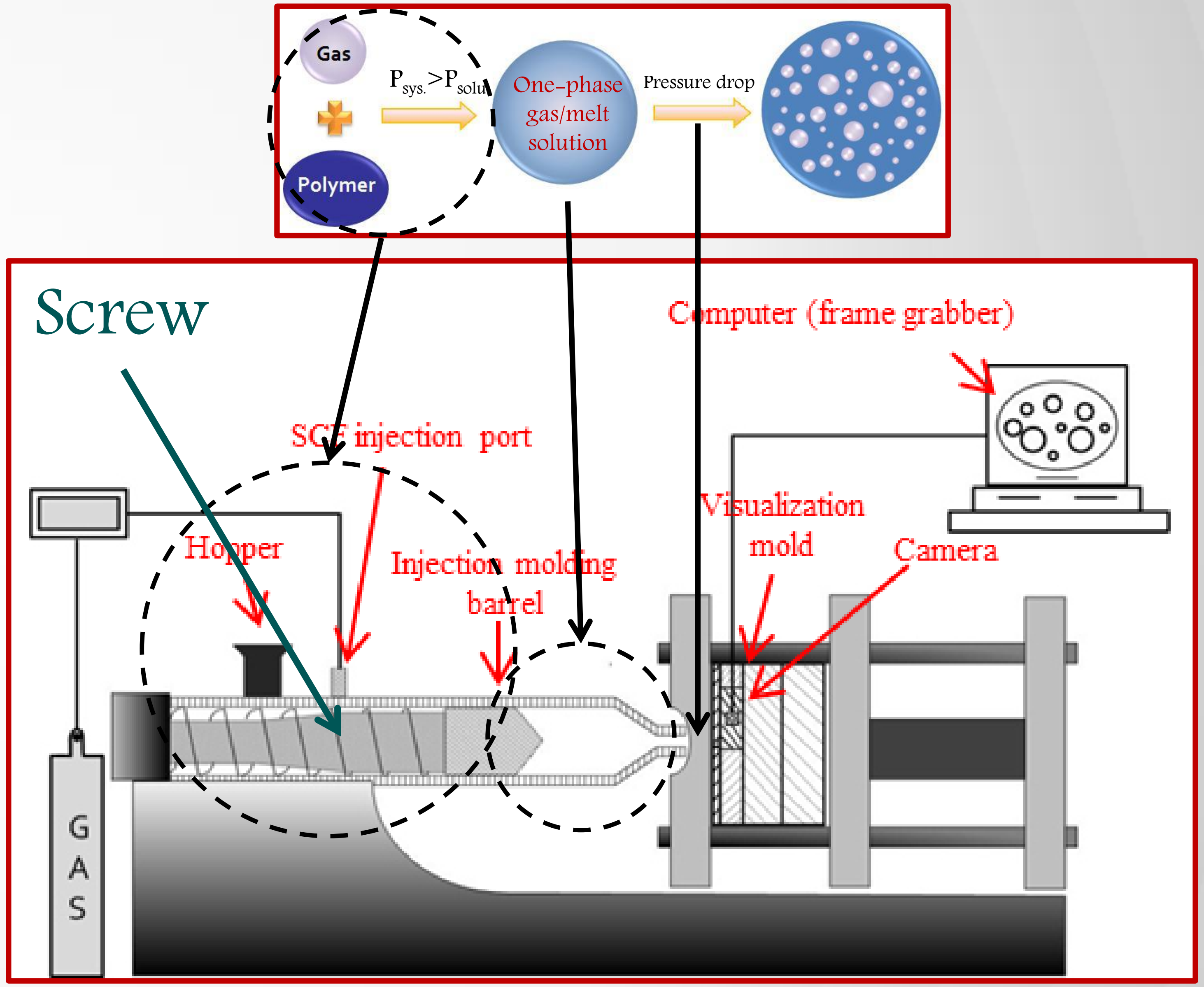




Diffusion-induced growth

$$R_{cr} = \frac{2\gamma}{P_{bub,cr} - P_{sys}}$$

Foam Injection Molding (FIM)



Foam Injection Molding (FIM)

Broad spectrum of applications

- ➢ almost no residual stresses;
- ➢ high geometric accuracy;
- ➢ sound insulation properties;

material/energy saving.

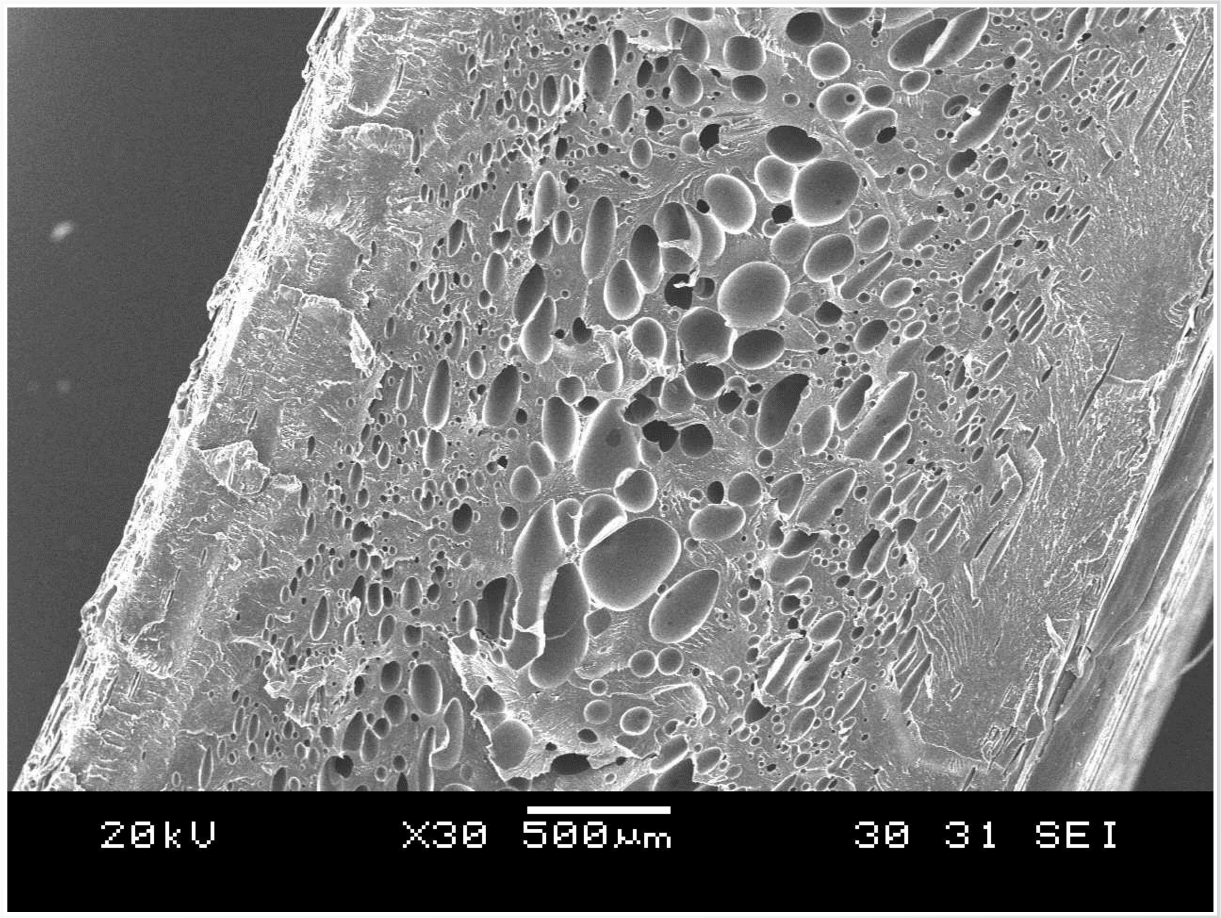
- ➢ higher toughness, impact strength, and fatigue life (micro-cellular)
- ➢ improved heat insulation(nano-cellular)

Challenges

- Control the morphology to obtain *desirable* properties
  - high cell density
  - uniform distribution

NOT easy in FIM !

Un-known
Mechanisms !



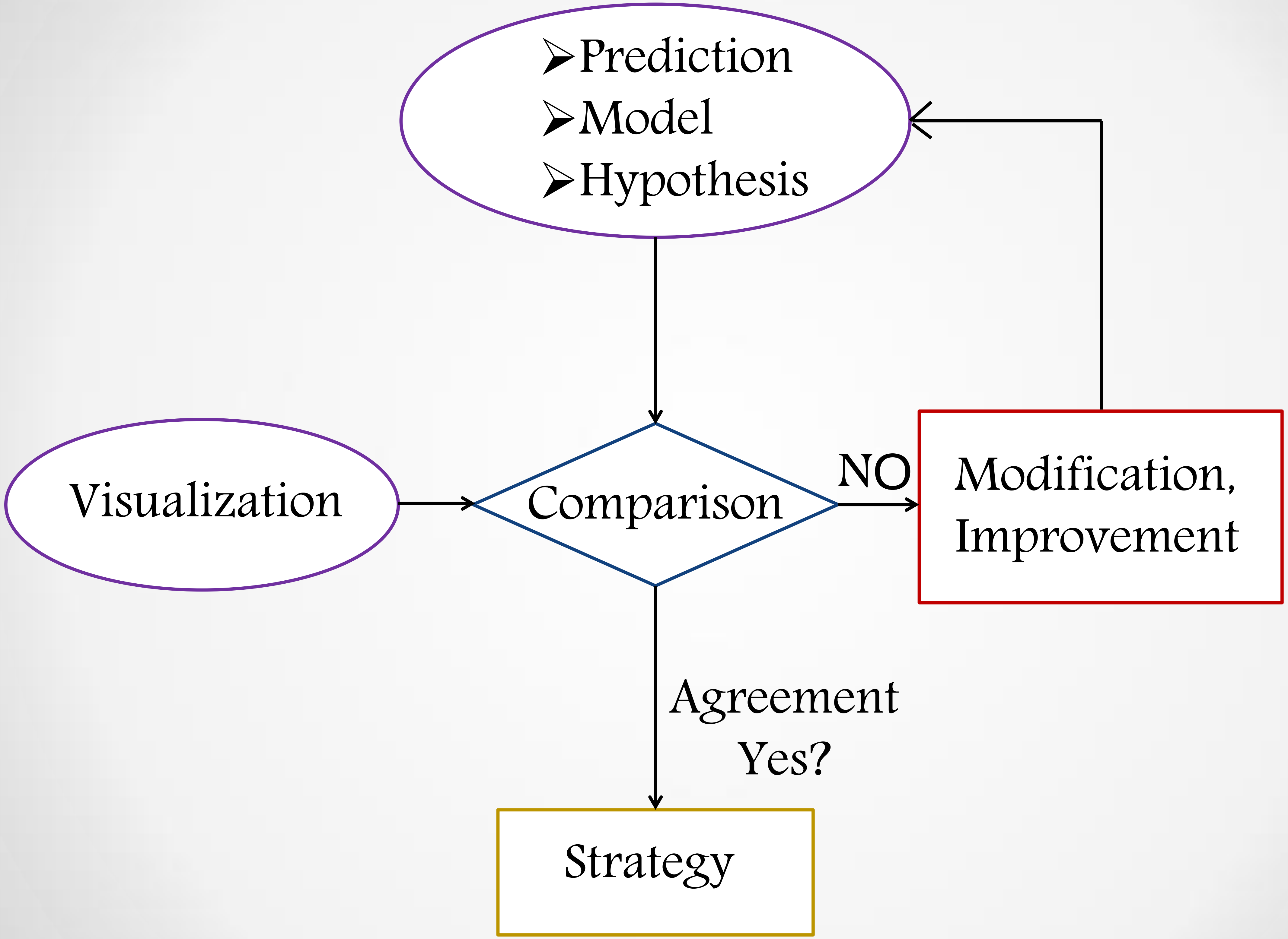
What we are trying to achieve?

Identify the underlying mechanisms (nucleation/growth) in various FIM technologies in order to:

1. Experiment
   - ✓ Set proper processing parameters to perform CORRECT experiment
   - ✓ To come up with DOE which yields the expected cellular structure (and so desired properties)

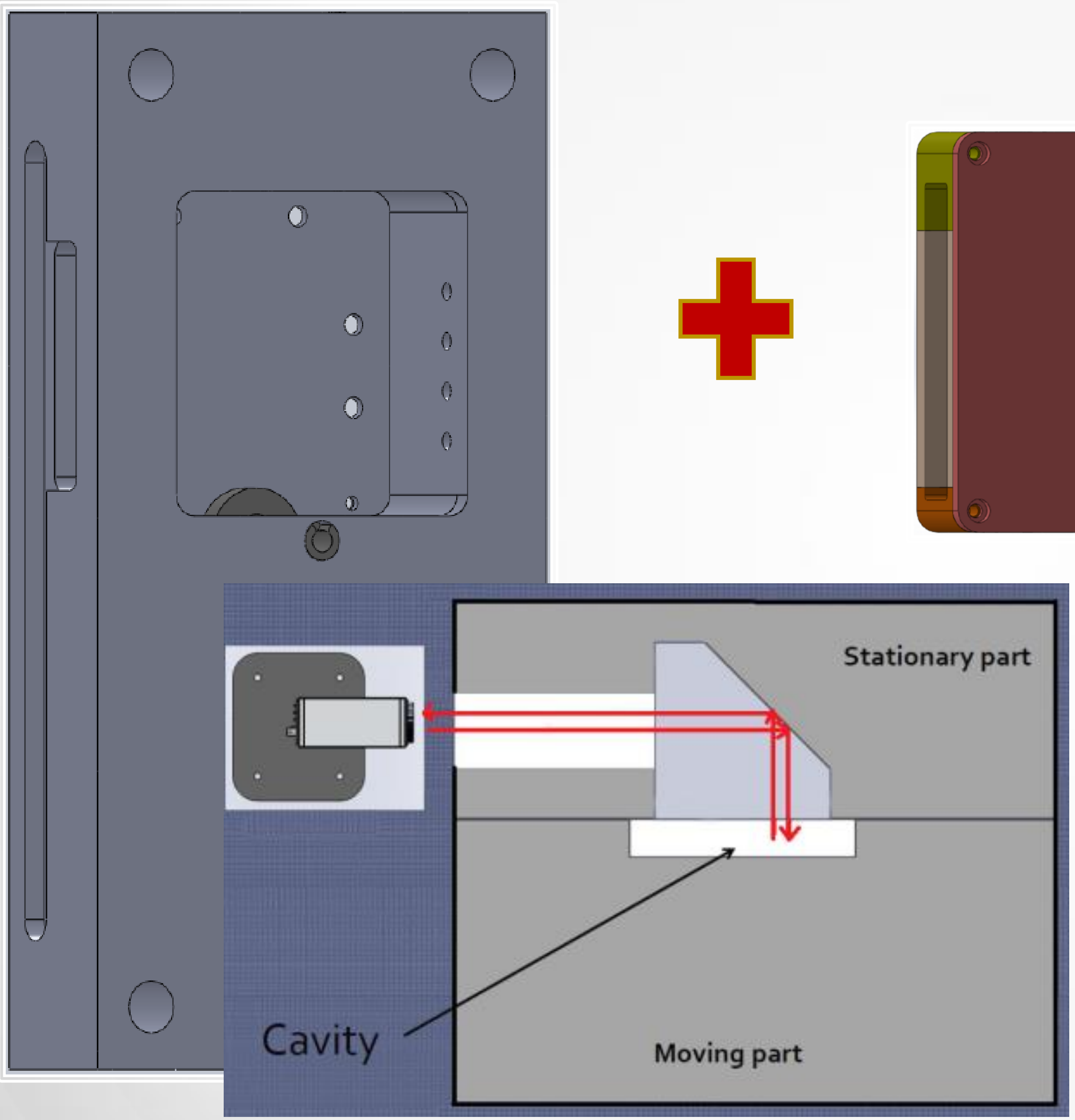
2. Simulation (Modeling)
   - ✓ Contributing parameters/responsible mechanisms to be included/considered
   - ✓ Actual (reliable) data to validate the model

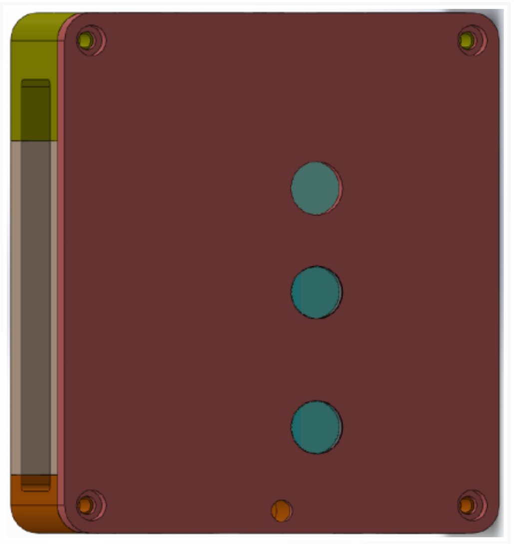
Our Research Approach

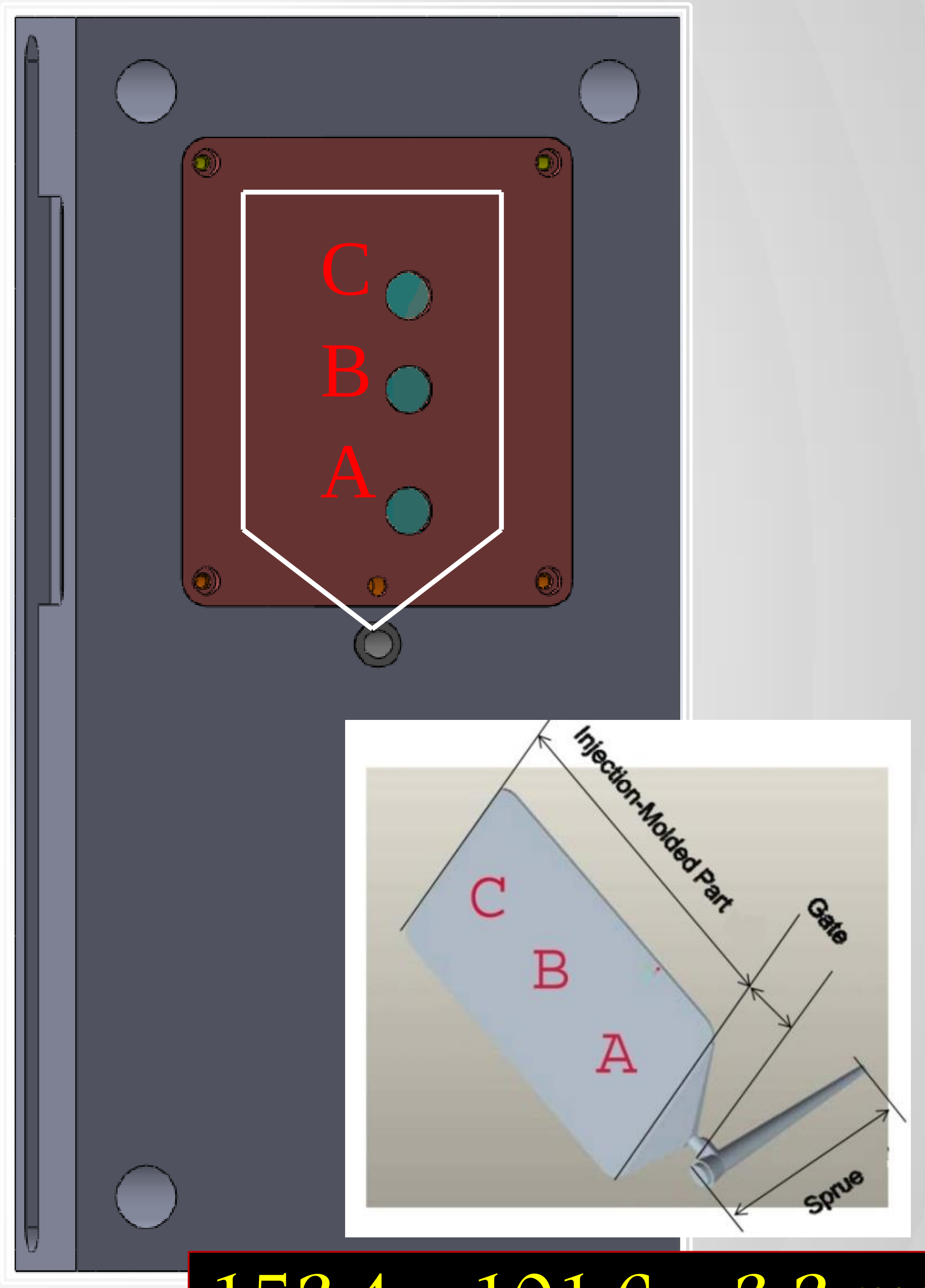


Visualization Mold Design and Experiment Equipment

Mold Design



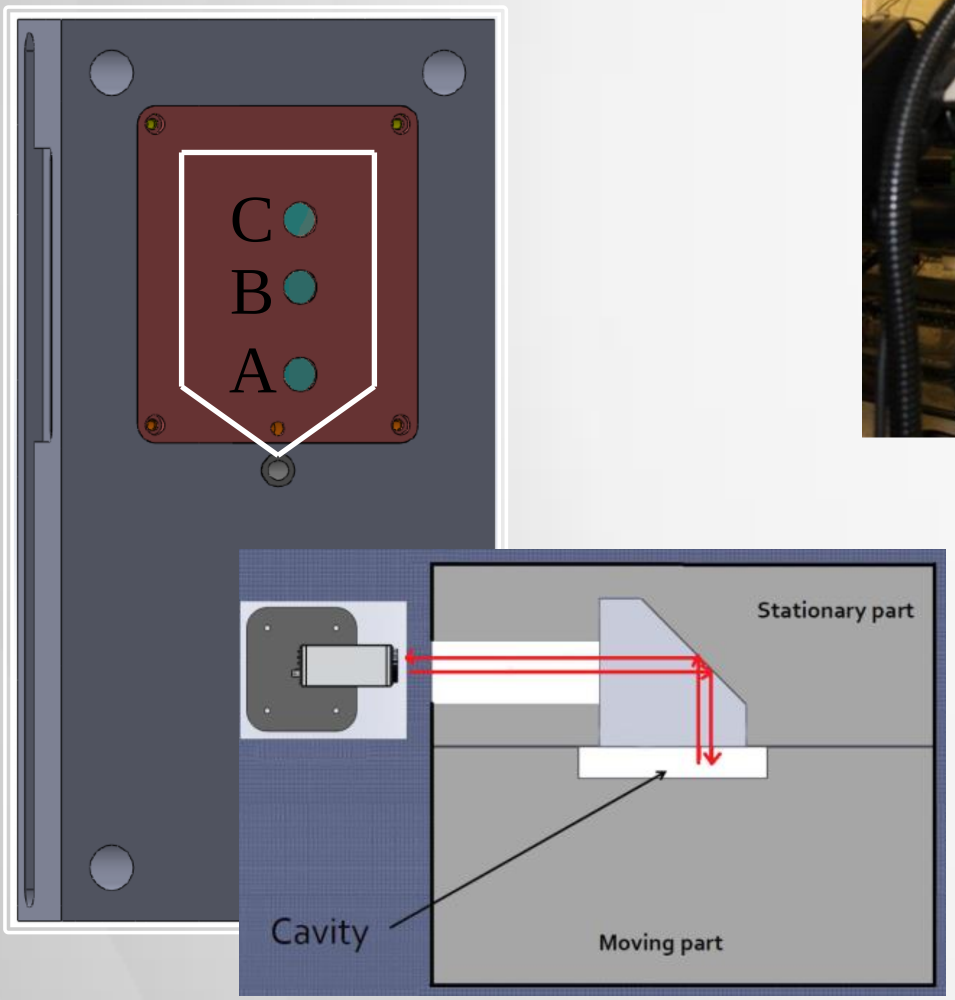


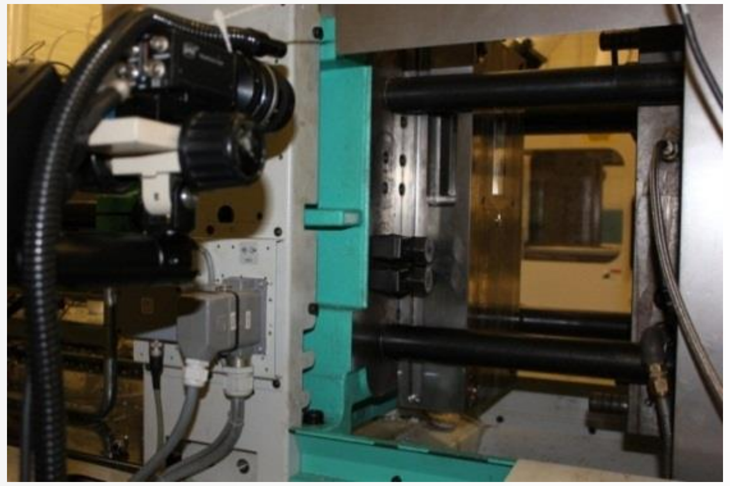


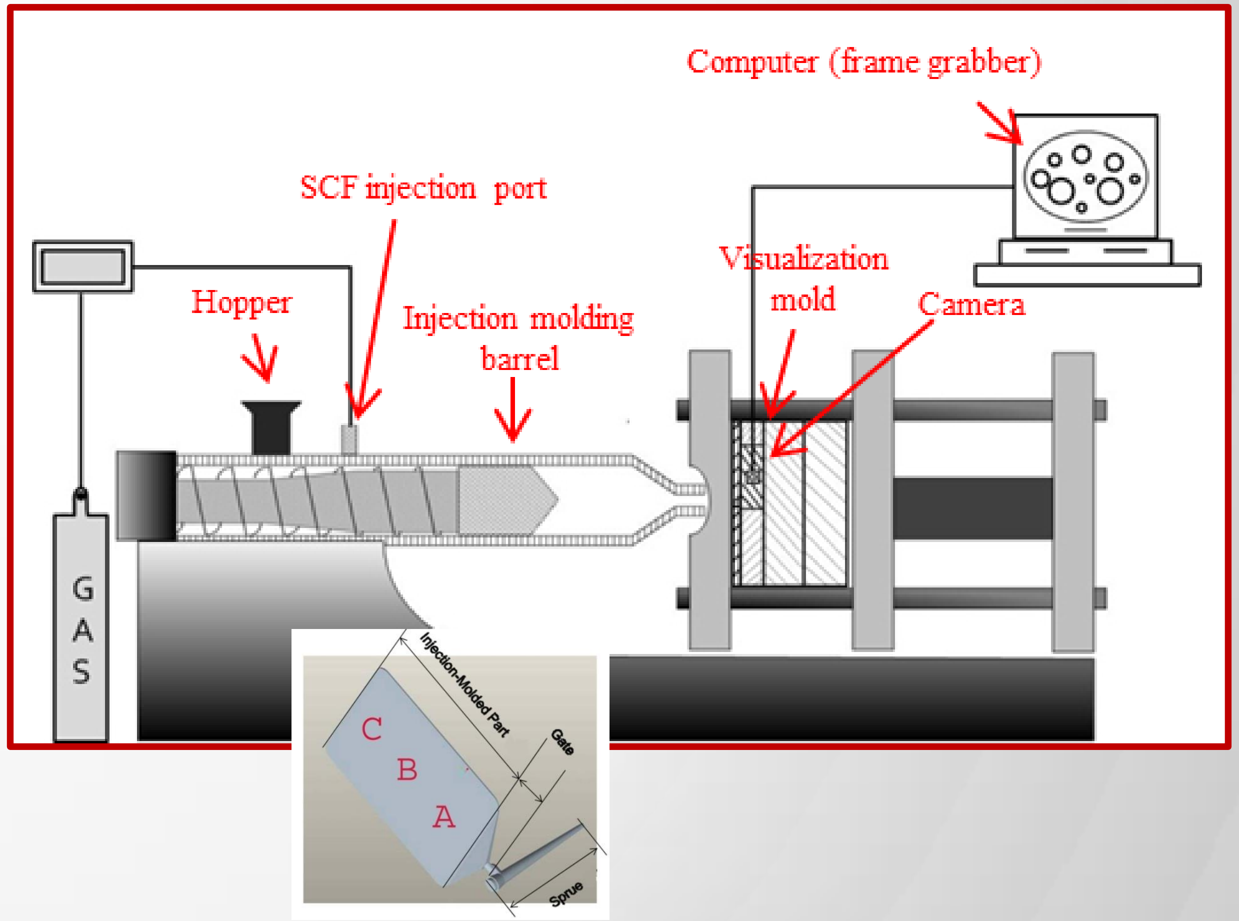
152.4 × 101.6 × 3.2 mm

Equipment

- 50-ton Arburg ALLROUNDER (equipped with MuCell)
- Visualization Mold
- Camera: CV M10 camera from JAI equipped with a magnifying lens from Navitar



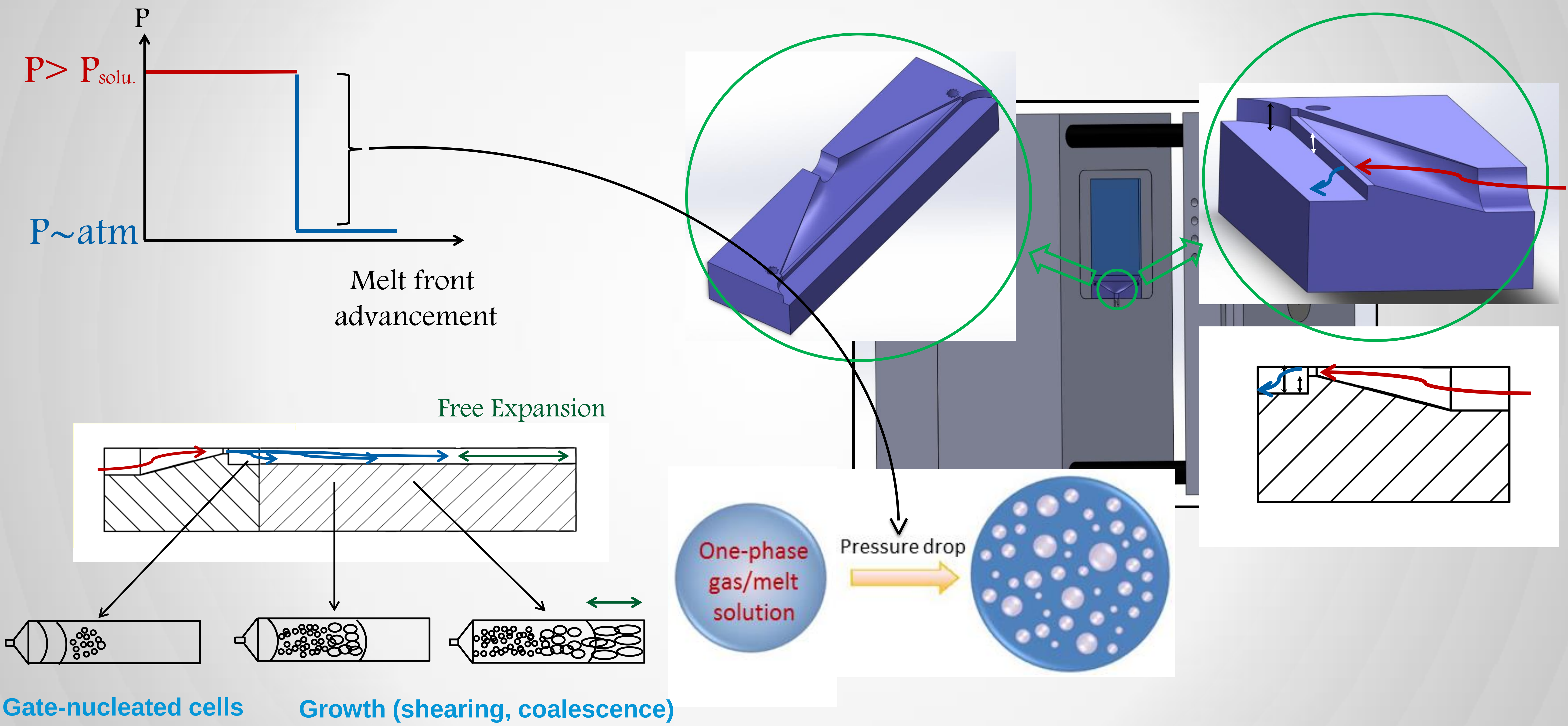




135 × 111 × 3.2 mm

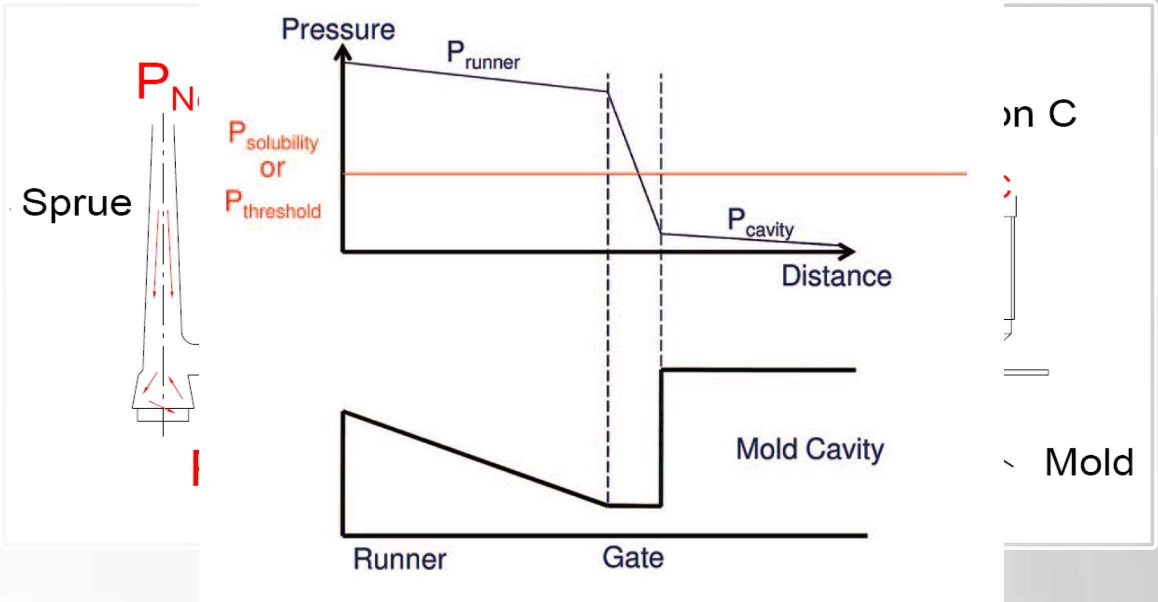
Low-pressure FIM

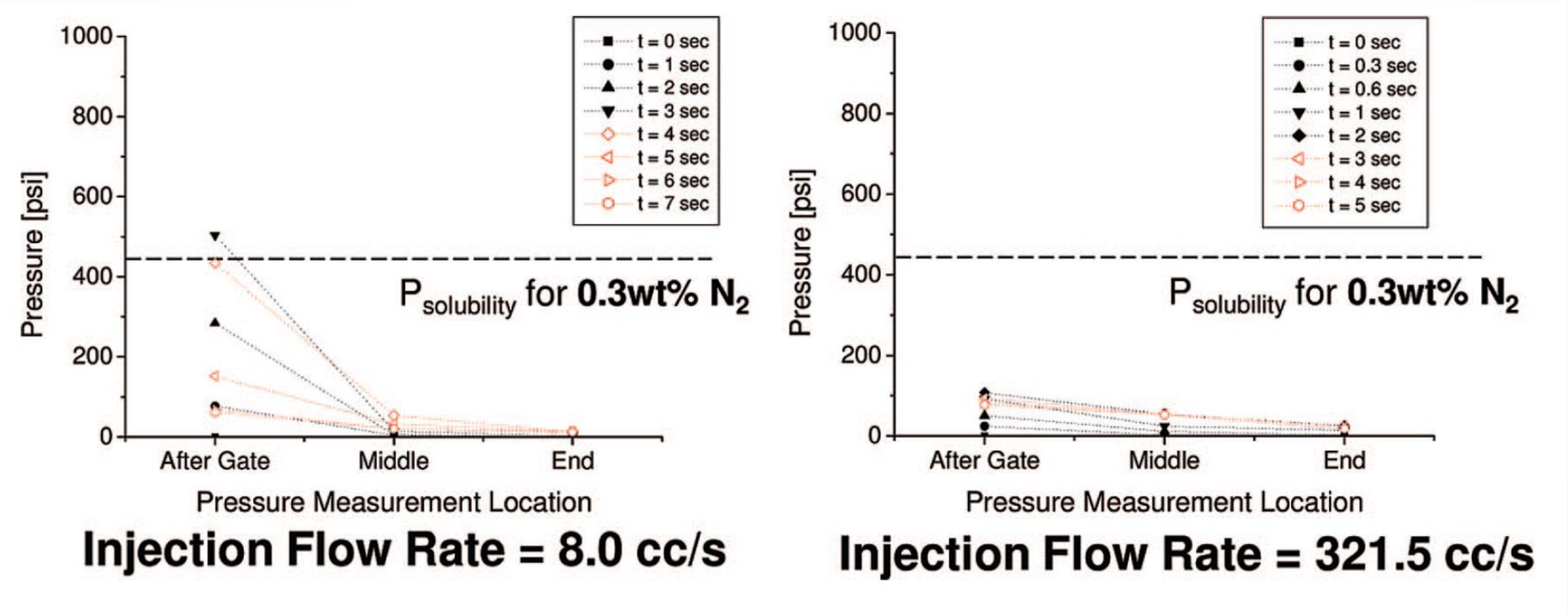
Pressure Drop over the Gate (Low-Pressure FIM)



Strategies to improve the microcellular structure

1. Injection Speed
   a- higher melt/gas mixture temperature → lower cavity pressure
   b- higher pressure drop rate
   c- faster travel of gate-nucleated cells → less growth/coalescence



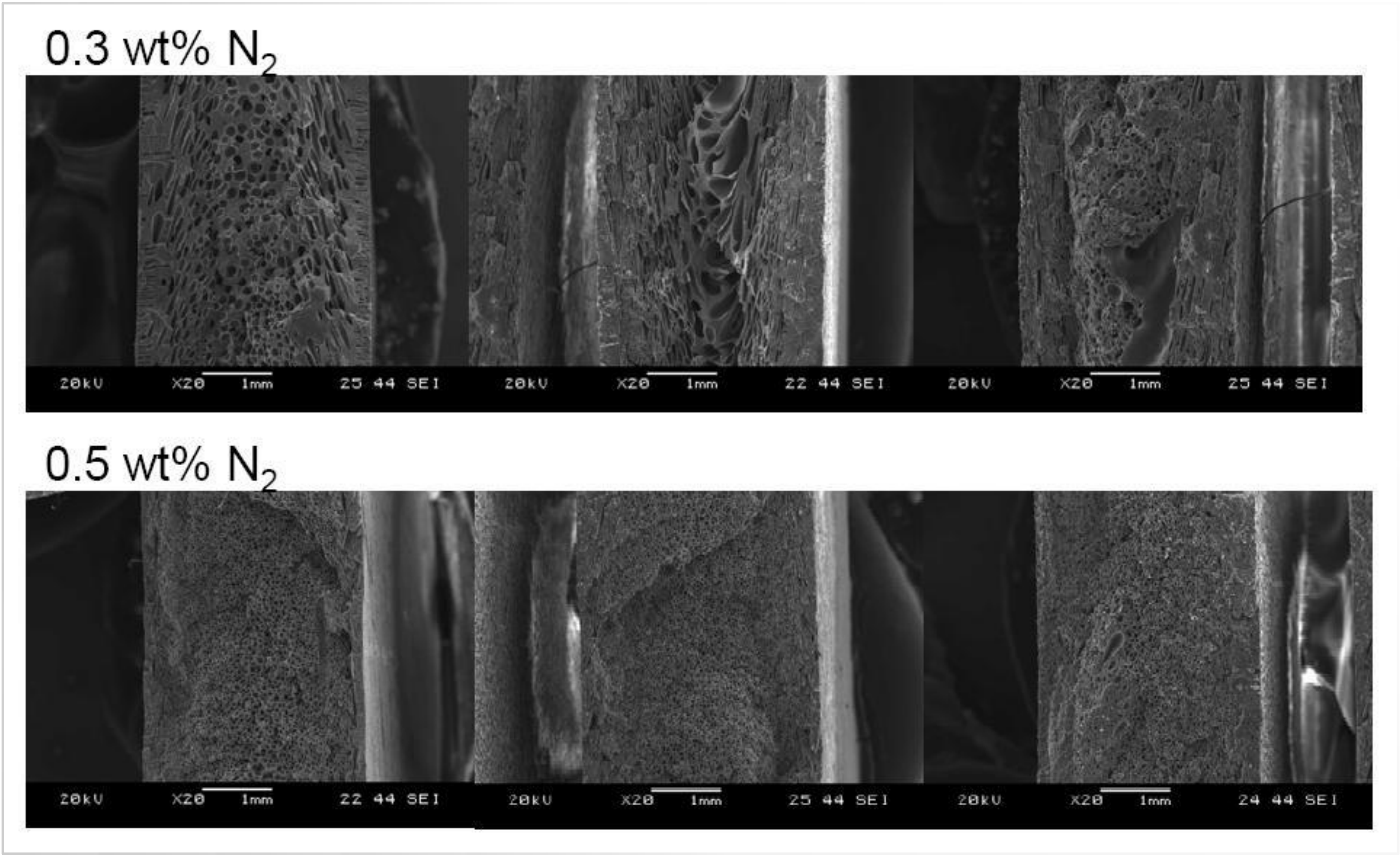


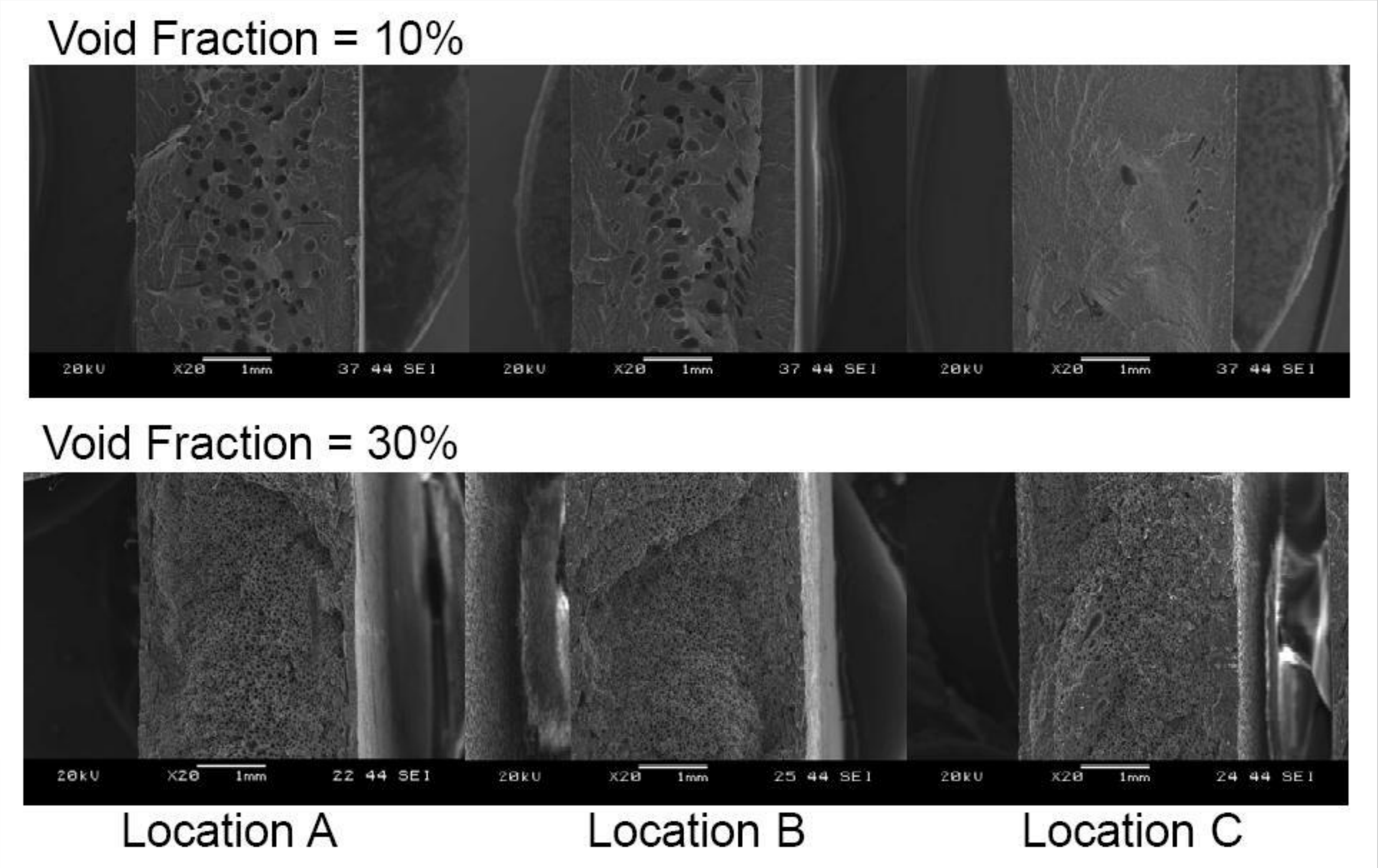
Lee, J. W., Wang, J., Yoon, J. D., & Park, C. B. (2008). Industrial & Engineering Chemistry Research, 47(23), 9457-9464

Strategies to improve the microcellular structure

2. Shot size

3. % of dissolved gas





0.5 wt% N_2, injection speed=400 mm/s, @200 °C

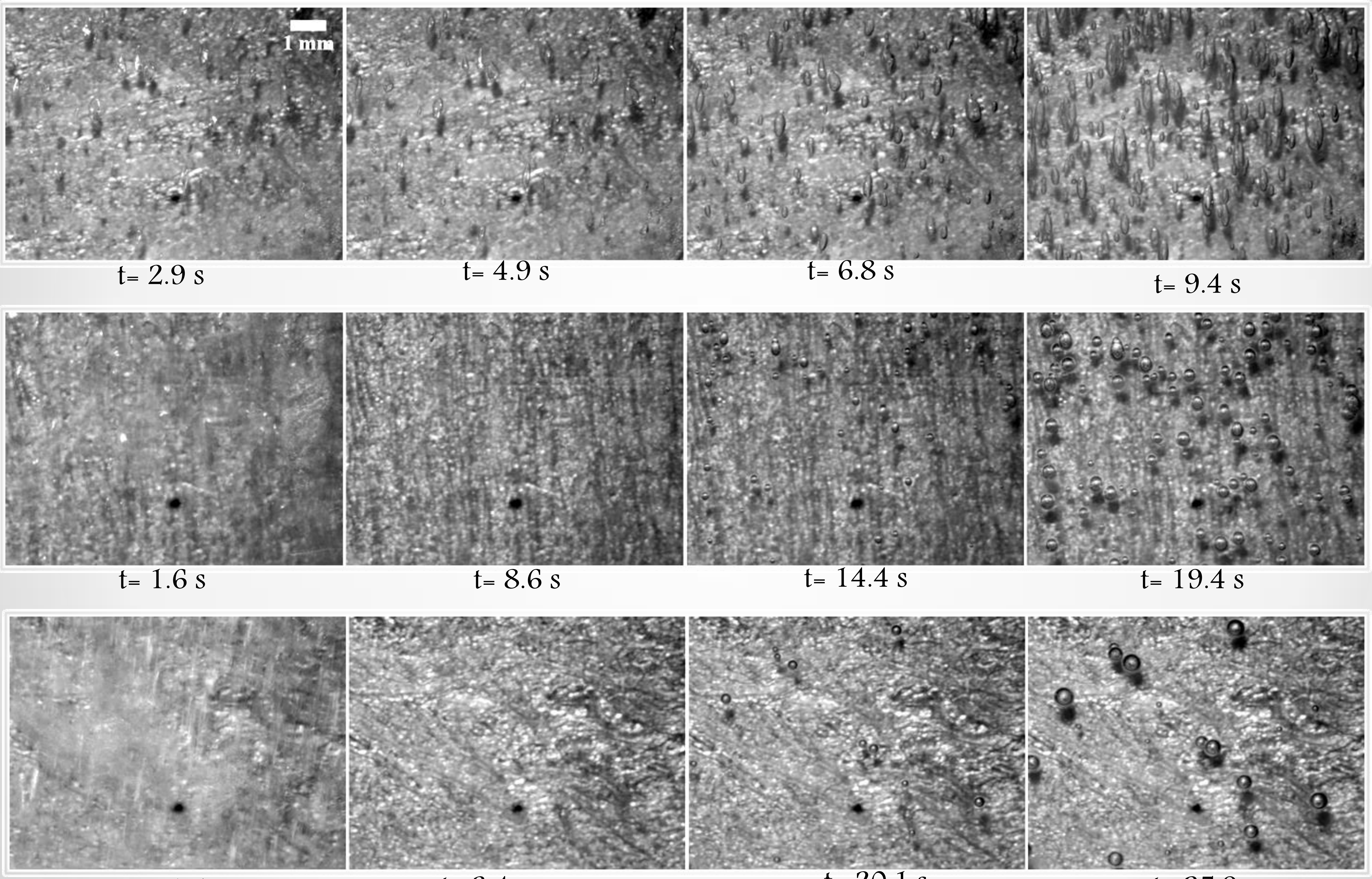
[1] Lee J. W. S., PhD Thesis, Chapter 5, Department of Mechanical and Industrial Engineering University of Toronto (2009)

High-pressure Foam Injection Molding

Materials:

- PS675 from AmericasStyrenics (MFI: 7.5 gr/10min);
- CO_2: Linde Gas Canada;

Low- and High-pressure FIM



Pack P= 25 bar

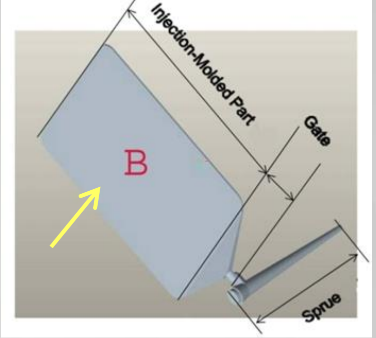
t= 2.9 s | t= 4.9 s | t= 6.8 s | t= 9.4 s

Pack P= 80 bar

t= 1.6 s | t= 8.6 s | t= 14.4 s | t= 19.4 s

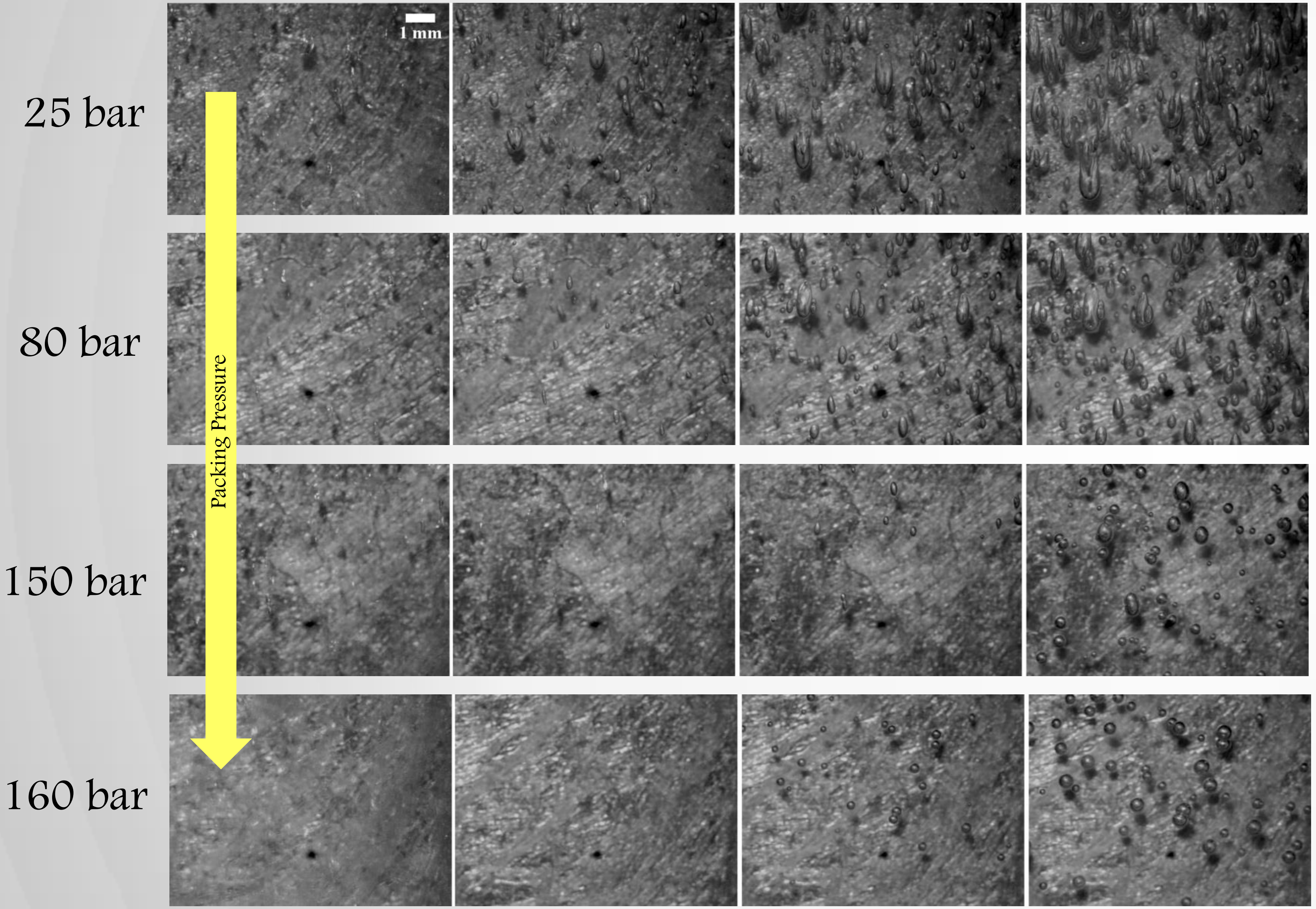
Pack P= 150 bar

t= 1.5 s | t= 3.4 s | t= 20.1 s | t= 25.9 s

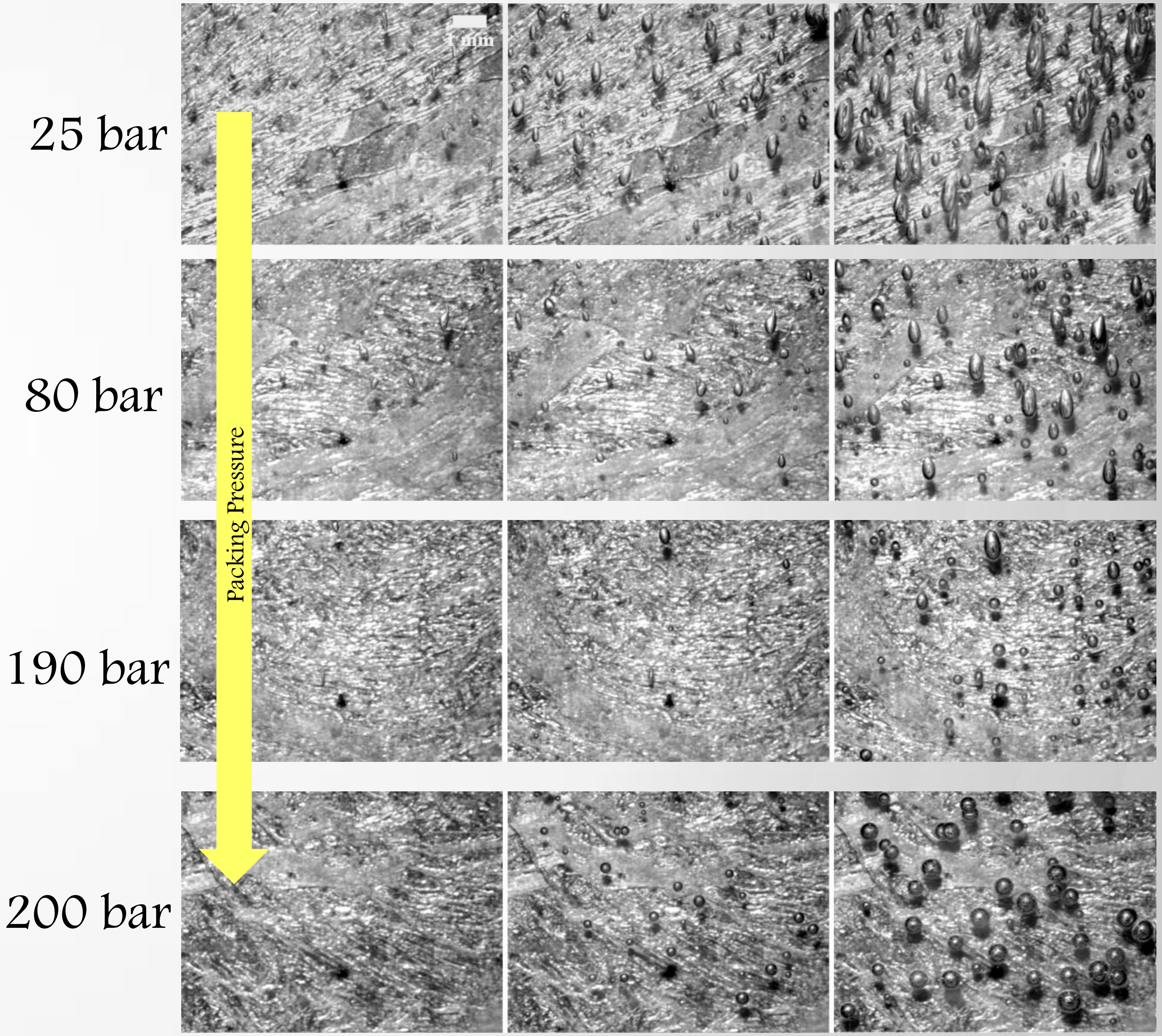


we are looking at this spot

Effect of Processing Parameters on Nucleation Mechanism in High-Pressure FIM



Injection speed 80 cm^3/s



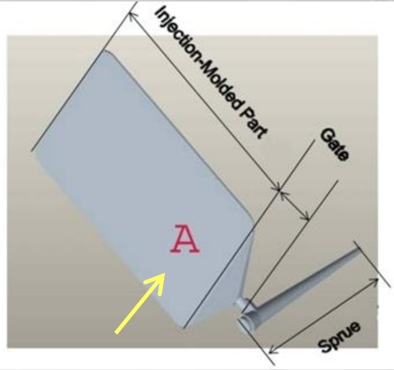
High-resistant gate

Mechanism of Bubble Formation using Gas-Counter Pressure

Materials:

- PS (MC3650) from AmericasStyrenics (MFI: 13.0 gr/10min);
- CO_2 & N_2: Linde Gas Canada;

Full-shot FIM + GCP

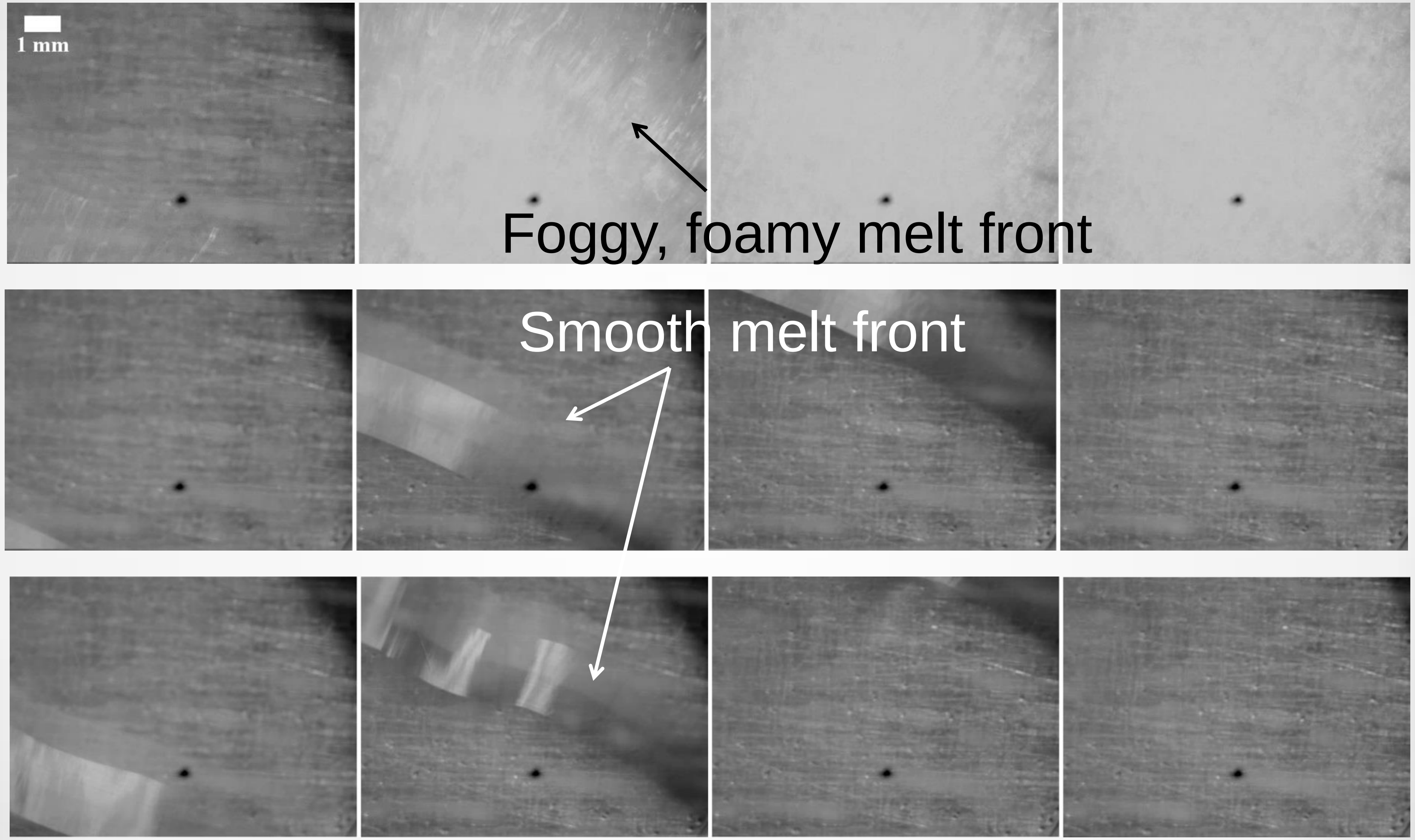


we are looking at this spot

NO GCP

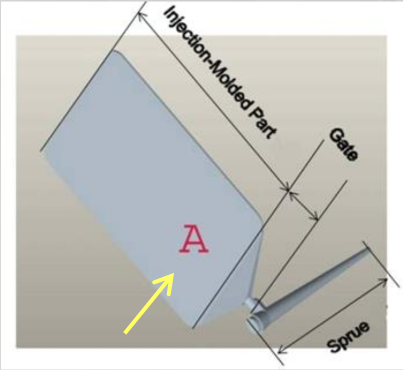
GCP= 200 psi

GCP= 400 psi

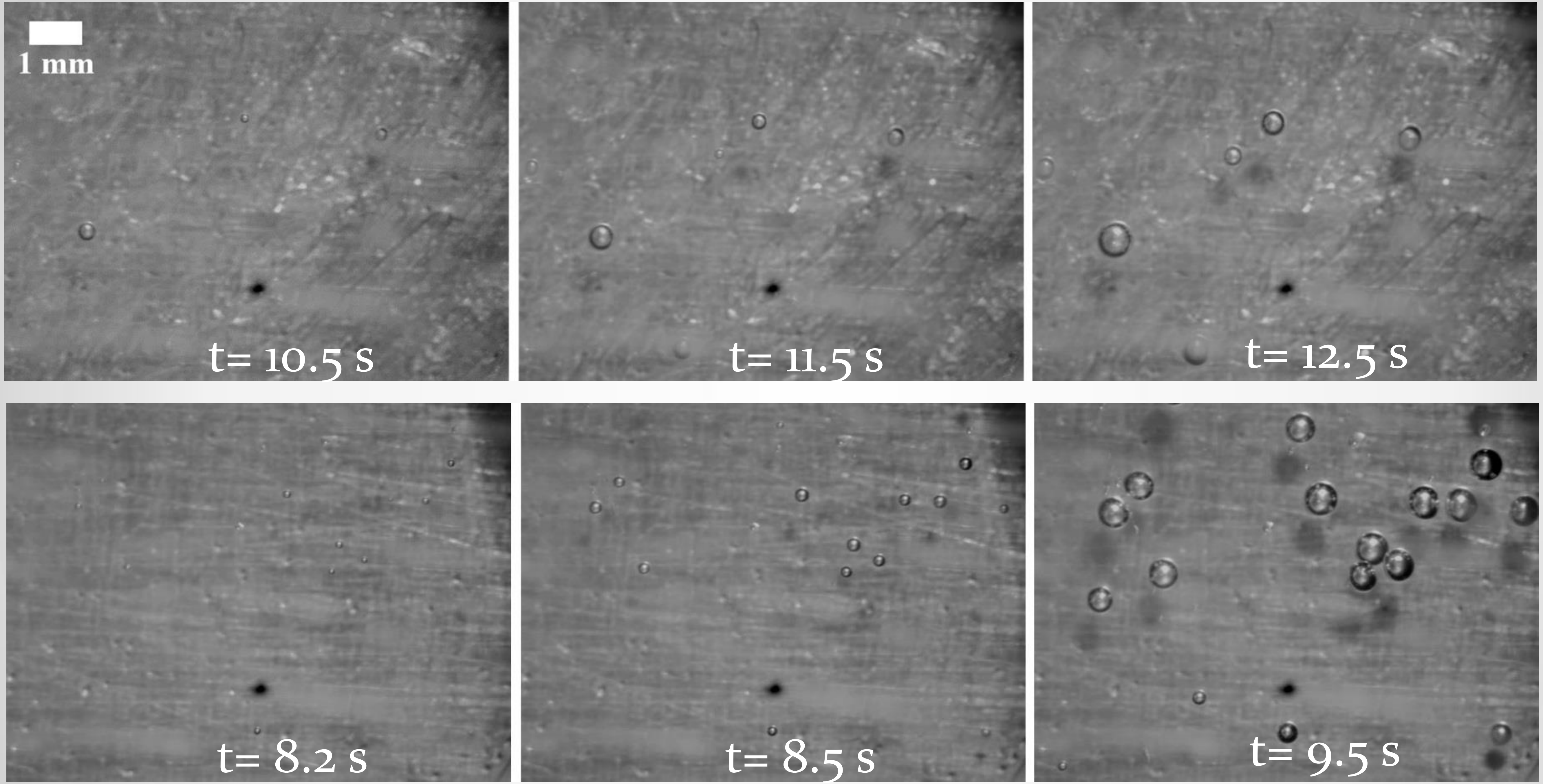


PS/CO_2 (1 % CO_2; Speed: 35 cc/s; T_{melt}: 230 °C)

Full-shot FIM + GCP



we are looking at this spot



PS/CO_2 (1 % CO_2; Speed: 35 cc/s; T_{melt}: 230 °C)

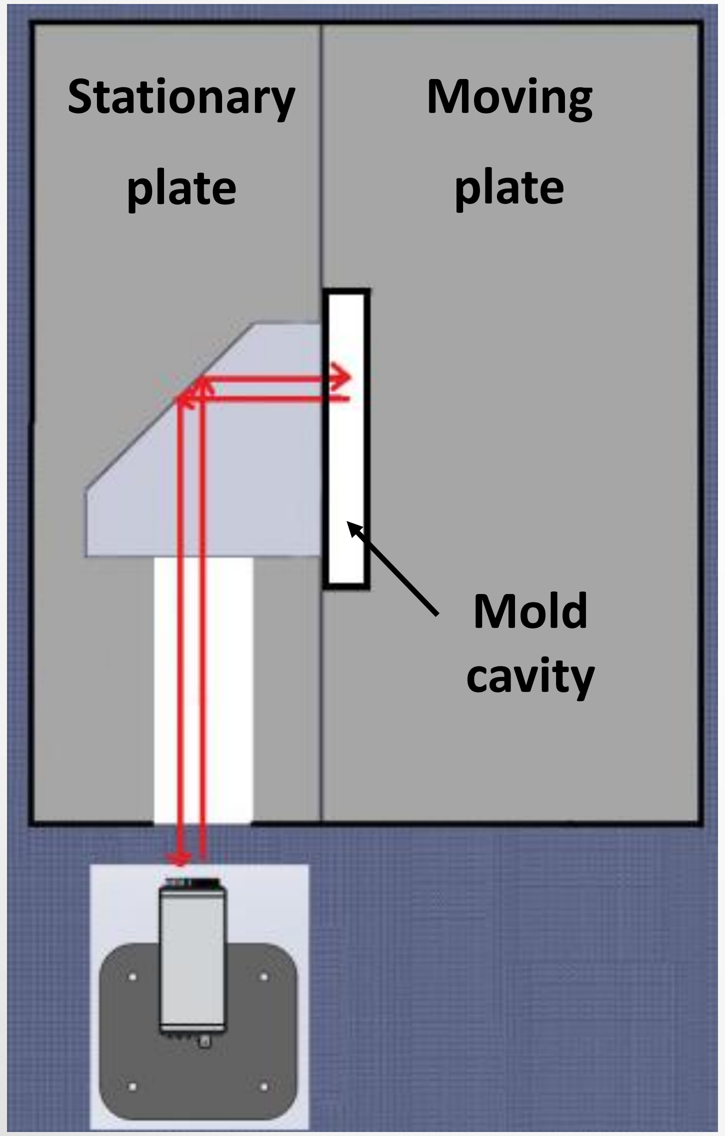
High-Pressure Foam Injection Molding with High Expansion

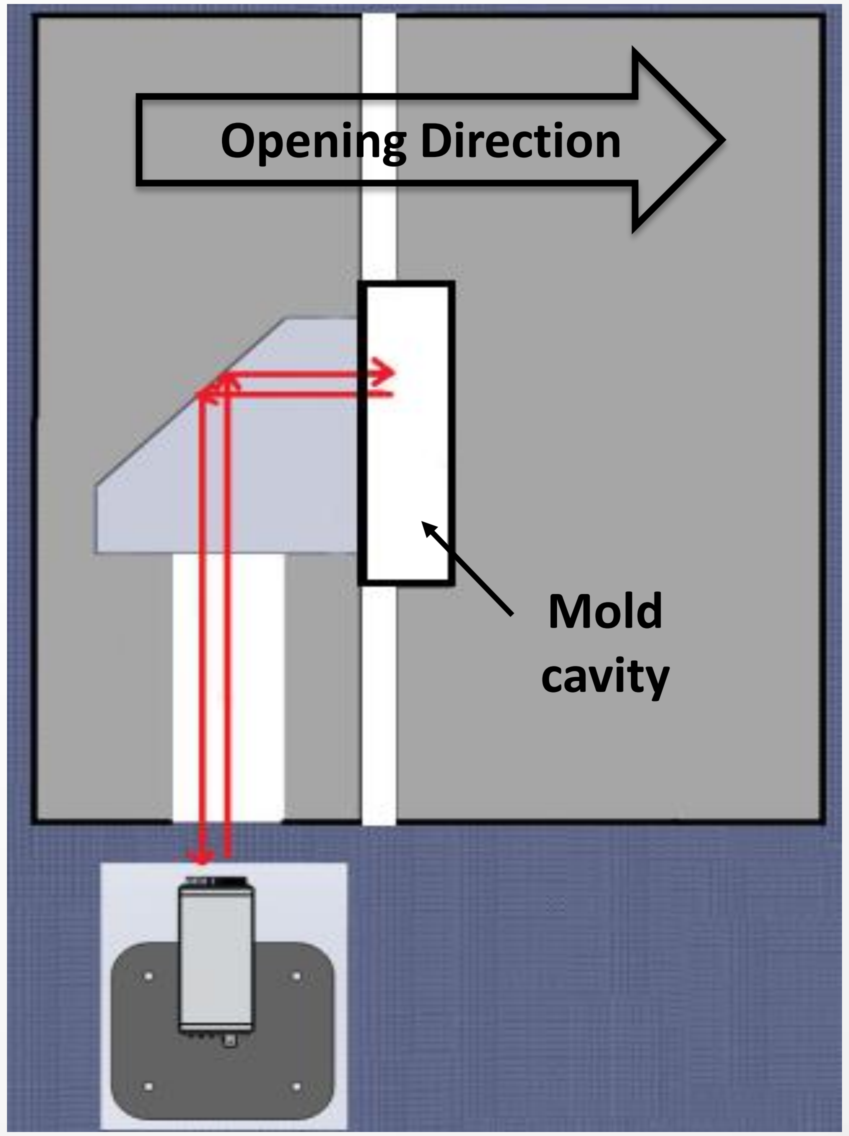
Materials:

- PS675 from AmericasStyrenics (MFI: 7.5 gr/10min);
- CO_2: Linde Gas Canada;

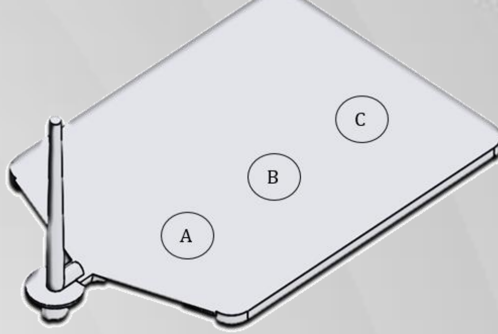
High-Pressure Foam Injection Molding with High Expansion

- To increase the void fraction (i.e., the expansion ratio)

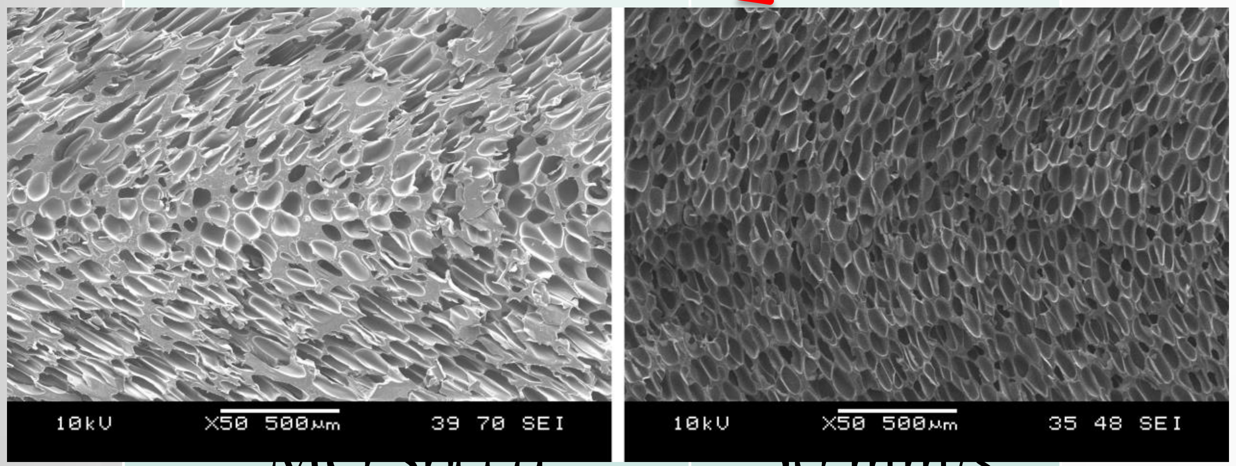


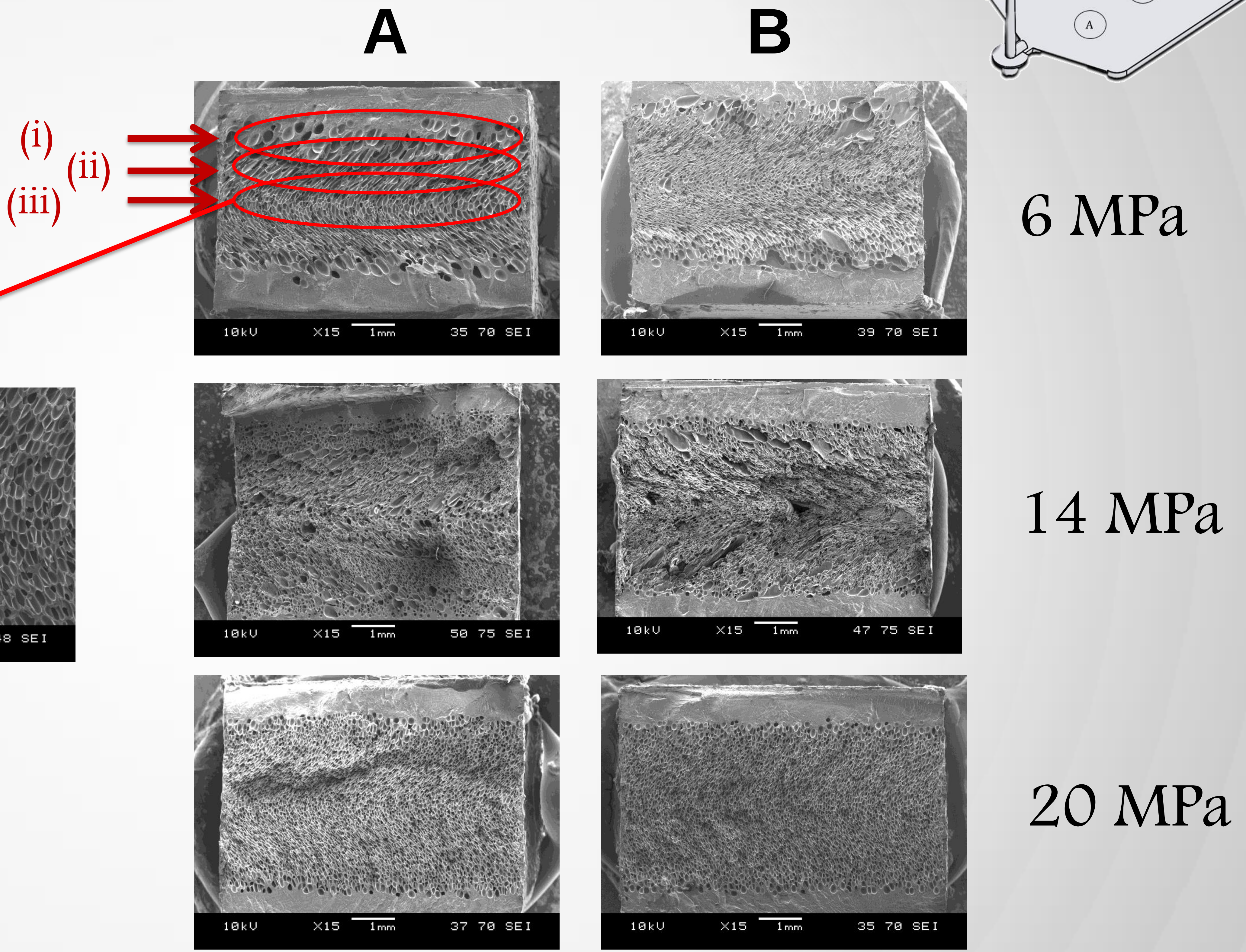


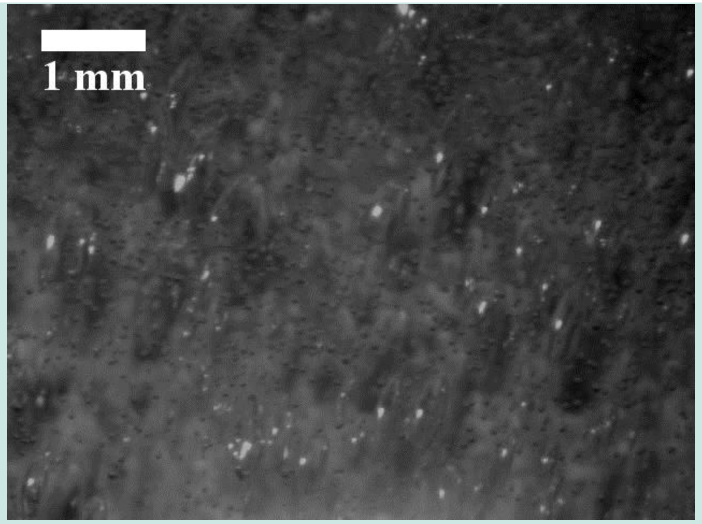
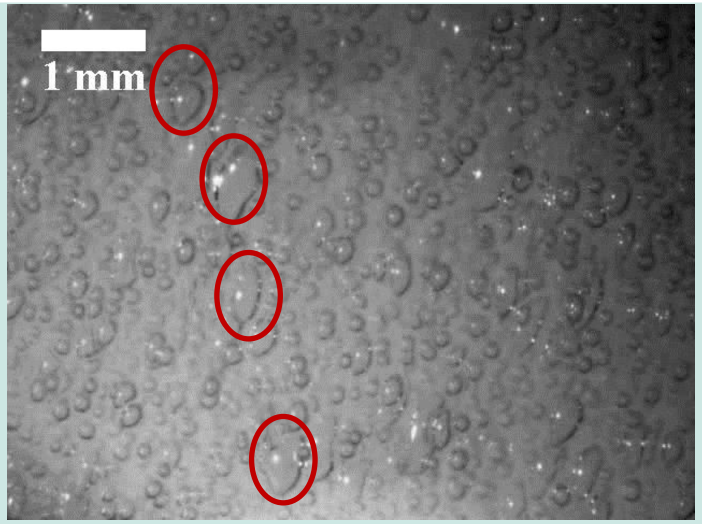
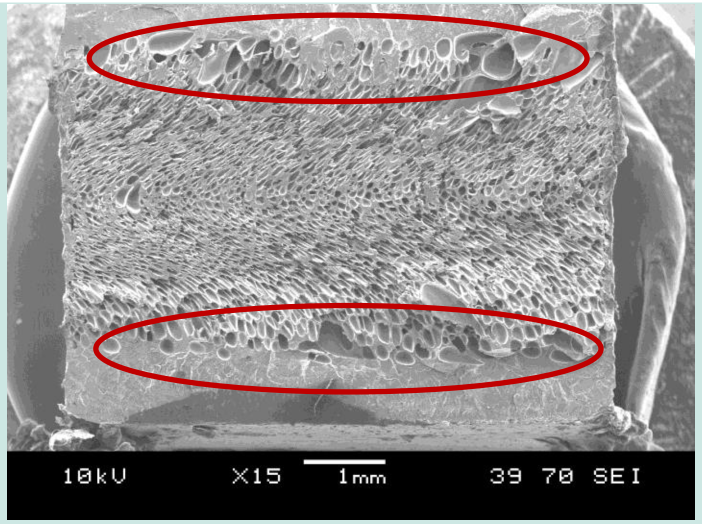
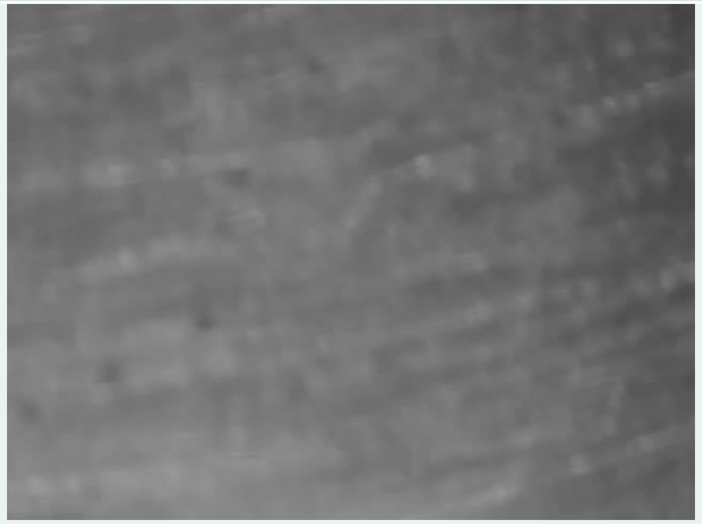
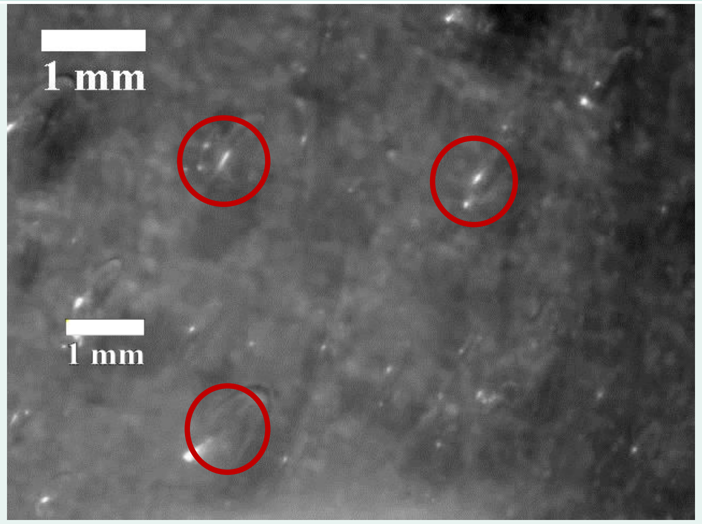
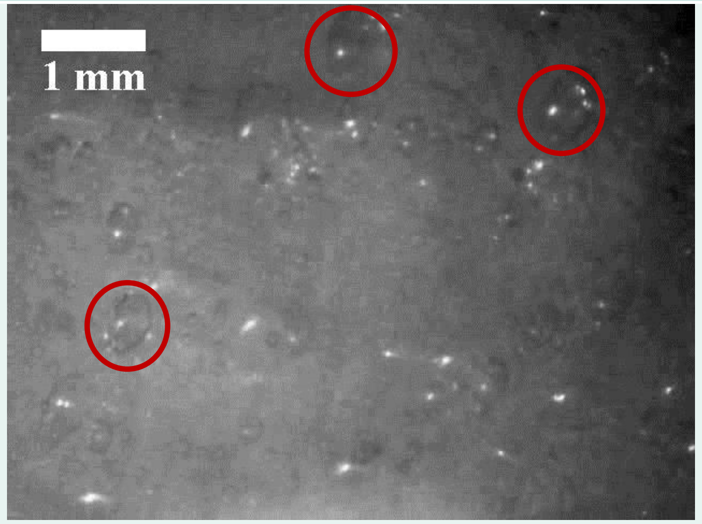
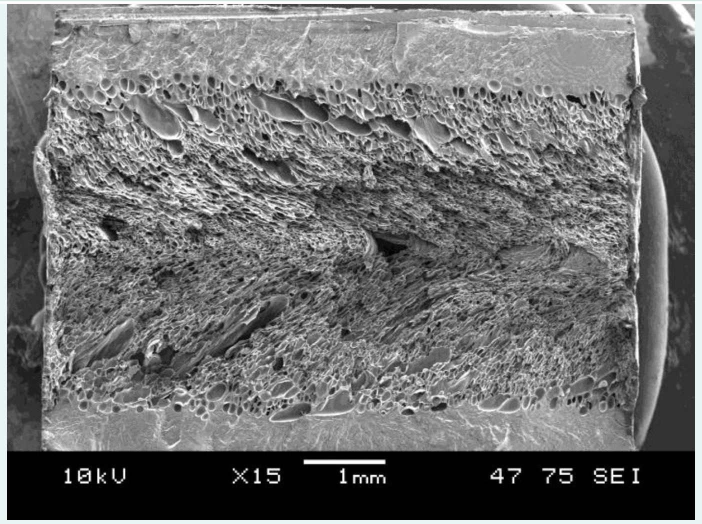
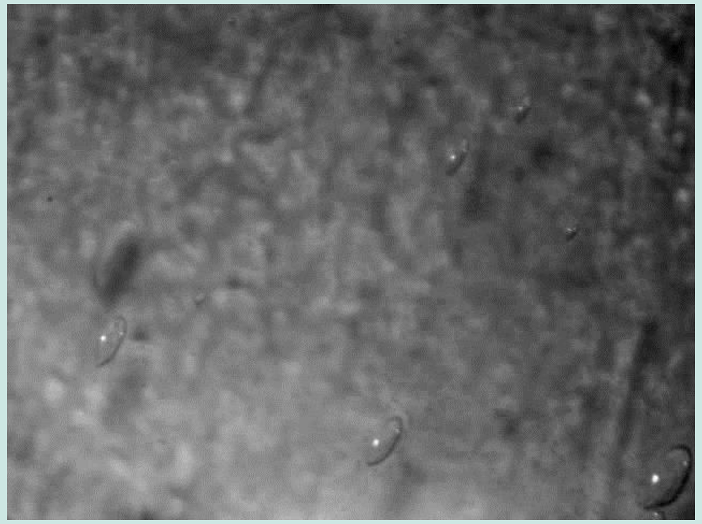
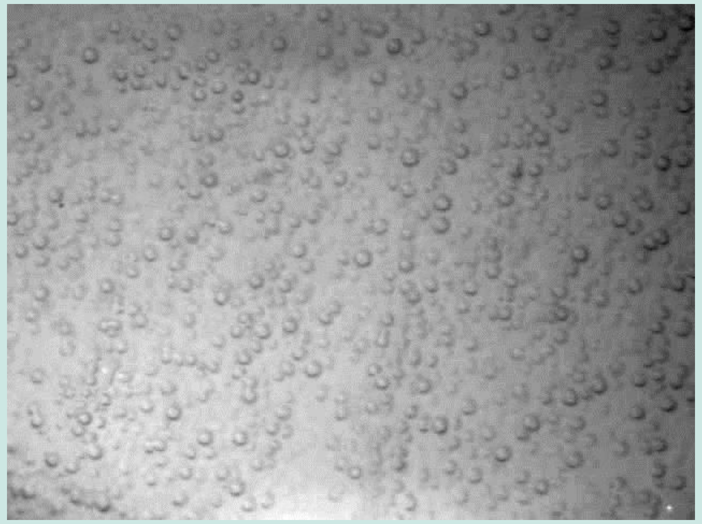
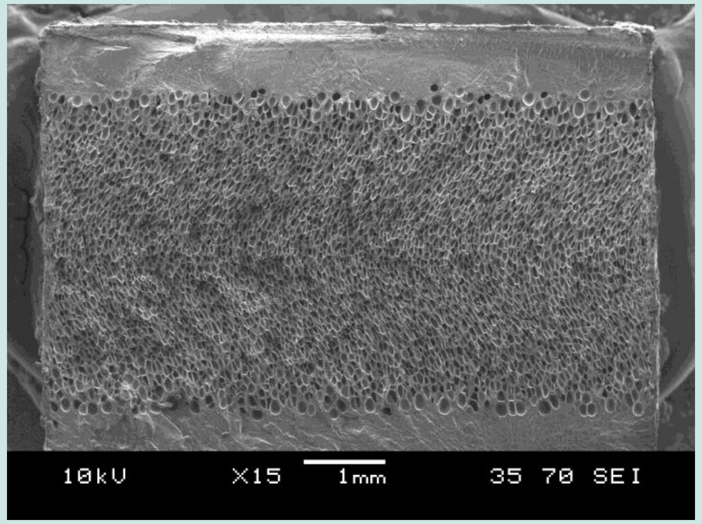
Experiment



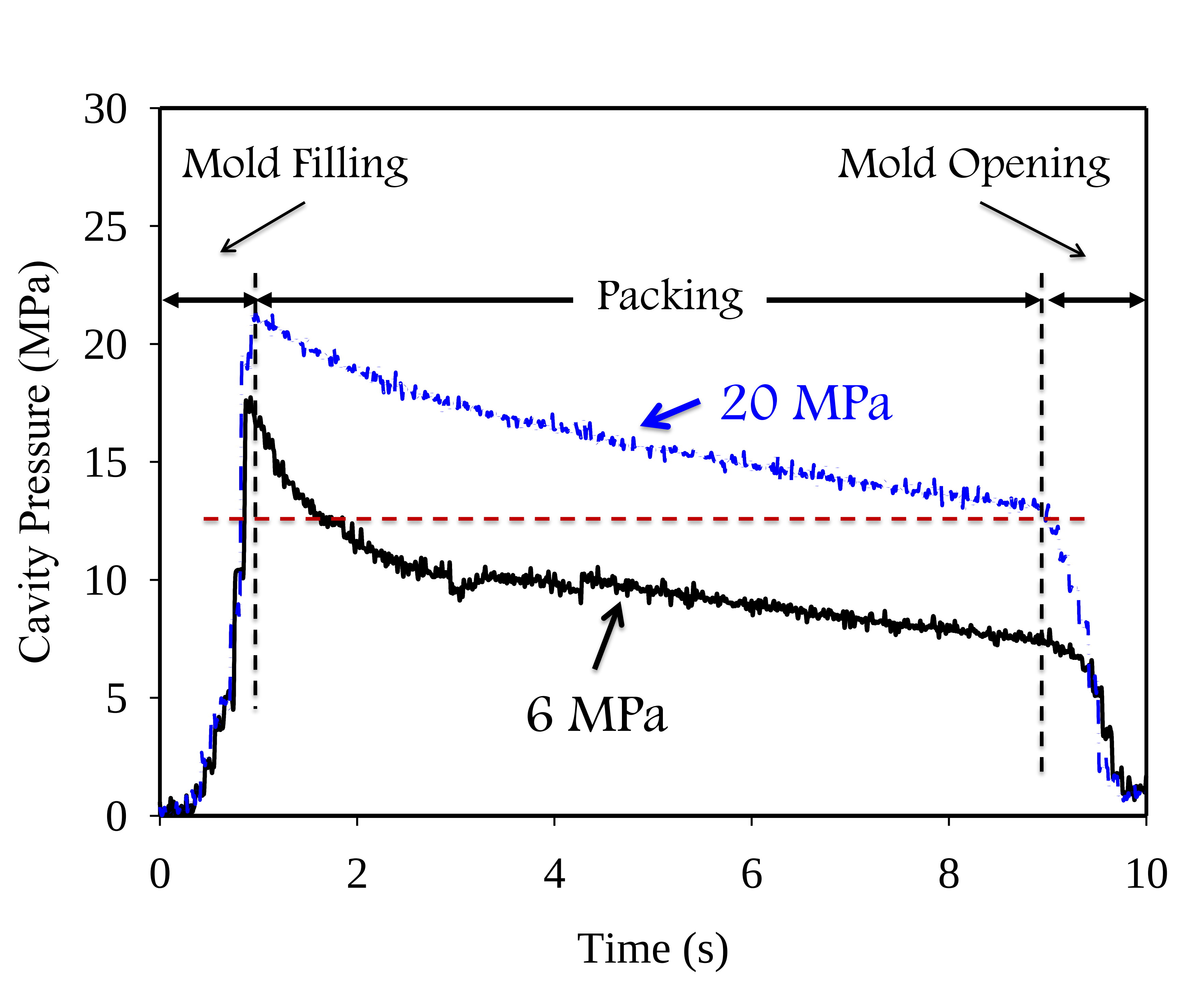
Processing parameter	Value
Shot Size	62 cm^3
Gas concentration	5% wt
MO Speed	[illegible] mm/s
MO Distance	2 mm
Cooling Time	30 s



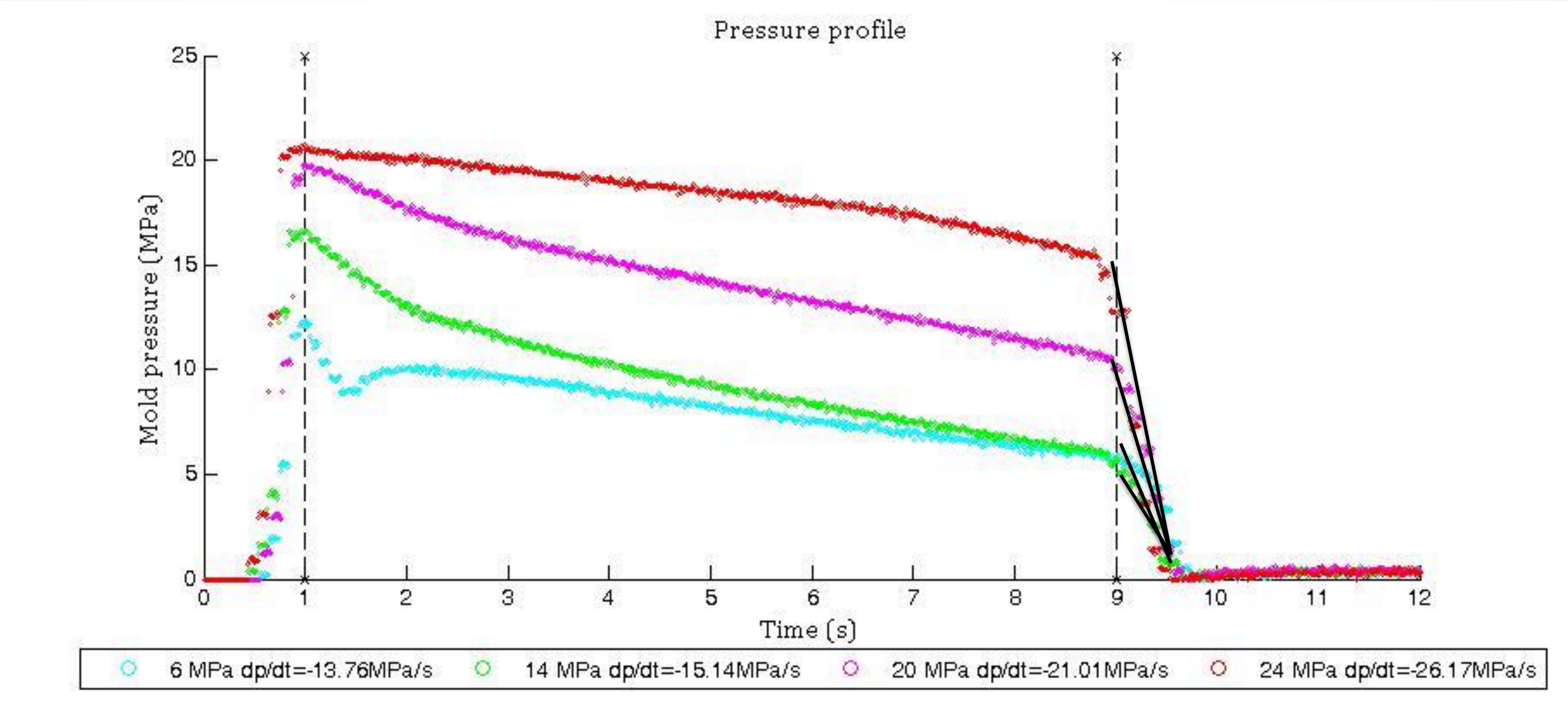


Packing Pressure	Video at Location B	Before MO (10.15s)	After MO (11.45s)	SEM at Location B
6 MPa				
14 MPa				
20 MPa				

Cavity Pressure Profiles



Pressure Drop rate



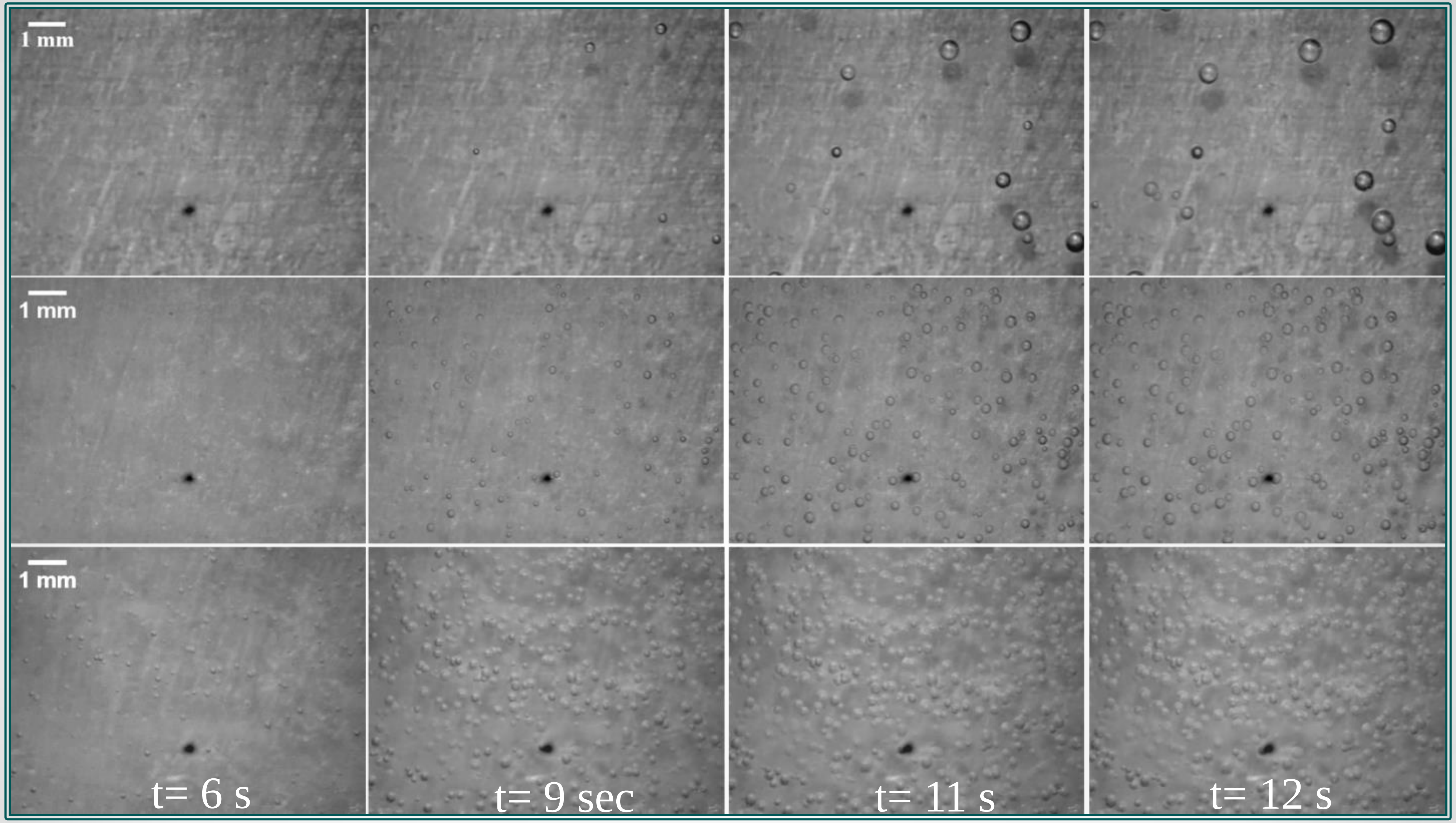
High-Pressure Foam Injection Molding with High Expansion

- High expansion
- Pressure-drop on the entire part → improved structural uniformity
- By removing all gate-nucleated bubbles (with application of proper packing pressure)
  - more gas supply for new nucleation (increased nucleation driving force)
  - no elongated bubble → improved homogeneity
  - proper packing pressure → higher pressure drop rate after opening → higher final cell density

Effect of Nucleating Agent (Talc)
&
Effect of Crystals

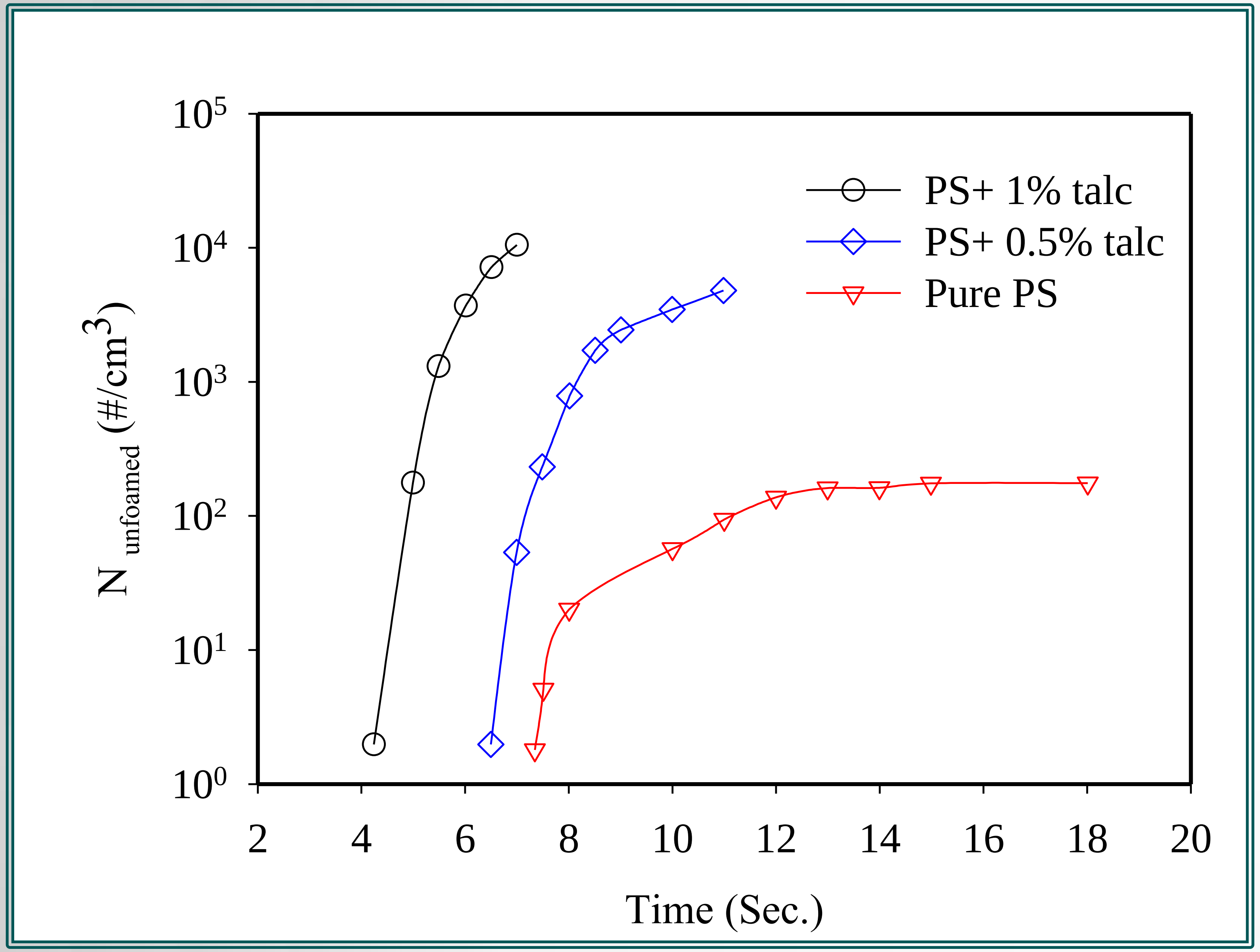
- PS675 from AmericasStyrenics (MFI: 7.5 gr/10min);
- PP DM55Pharm, Borealis (MFI: 2.8 gr/10min, Homopolymer);
- CO_2: Linde Gas Canada

High-Pressure Foam Injection Molding using Talc



PS/CO_2 (1% CO_2; Speed: 80 cc/s; T_{melt}: 230 °C)

High-Pressure Foam Injection Molding using Talc



$$w_{hom} = \frac{16\,\gamma^3}{3\,(P_{bub,cr} - (P_{sys} + \Delta P_{local}))^2}$$

$$w_{het} = w_{hom}\; F(\theta_c, \beta)$$

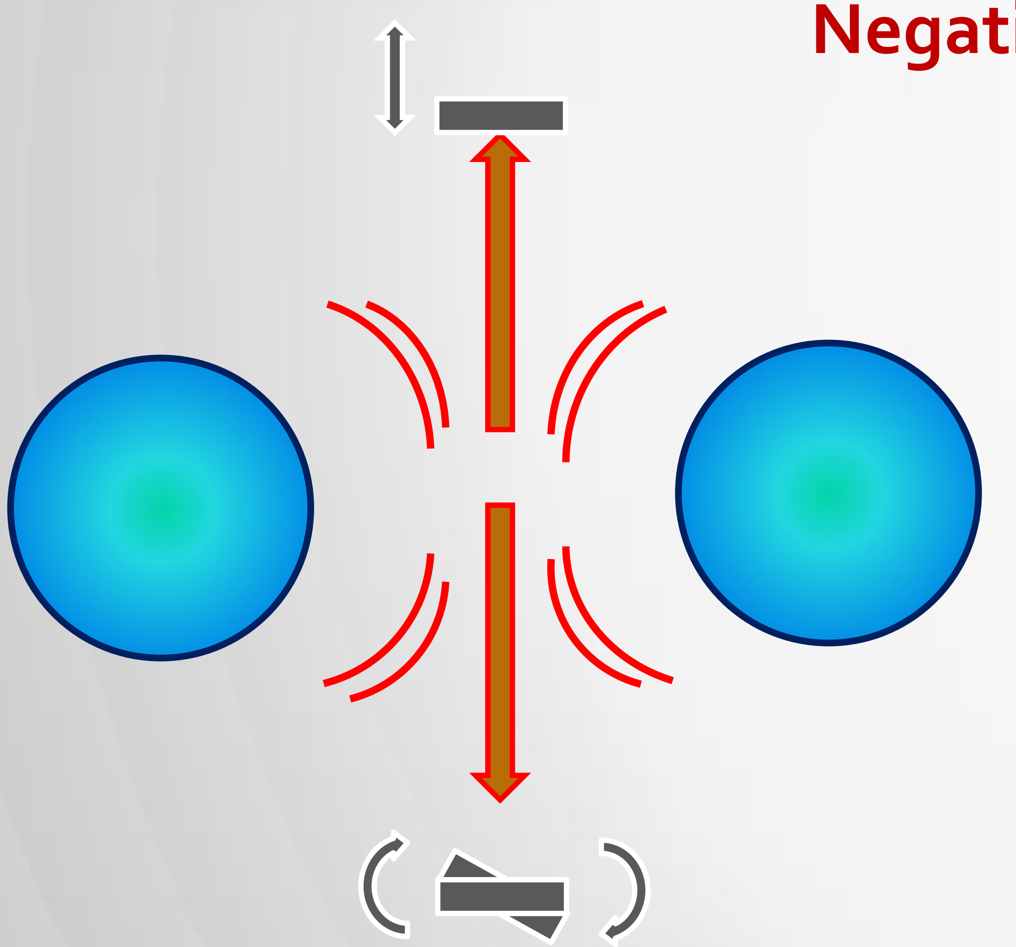
$$F(\theta_c, \beta) \leq 1$$

$$F(\theta_c, \beta) = \frac{1}{4}\left[2 - 2\sin(\theta_c - \beta) + \frac{\cos\theta_c \cos^2(\theta_c - \beta)}{\sin\beta}\right]$$

Importance of Nucleating Agents (Talc, Crystal)

- Heterogeneous nucleation $w_{het} = w_{hom}\, F(\theta_c, \beta);\ F(\theta_c, \beta) \leq 1$
- Pressure fluctuations about the exclusion

Bubble expansion → tangential stretching on the bubble wall → flow field in the surroundings



Negative local pressure fluctuations (tensile)

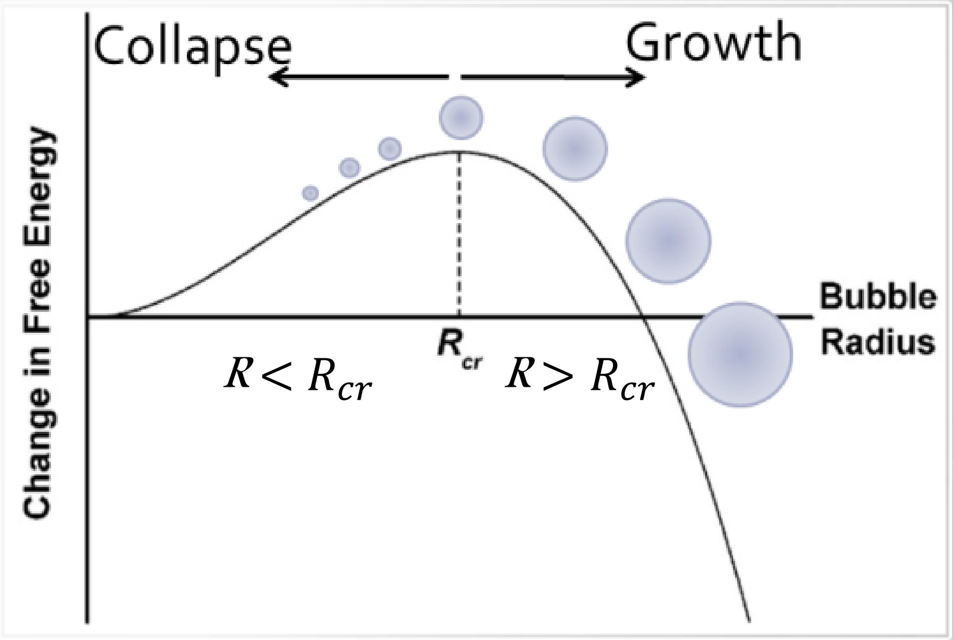
$$R_{cr} = \frac{2\gamma}{P_{bub,cr} - (P_{sys} + \Delta P_{local})}$$

⇓

Level of supersaturation ↑

⇓

Formation of baby bubbles



$$R_{cr} = \frac{2\gamma}{P_{bub,cr} - P_{sys}}$$

Summary

Low-pressure FIM: Gate-nucleated cells; high void fraction; poor structural uniformity and fair cell density

High-pressure FIM: Shrinkage-induced cells; improved structural uniformity; low void fraction and cell density

FIM+GCP: Nucleation upon GCP release; fast cell nucleation; improved surface quality;

High-pressure FIM+MO: Cell nucleation during MO, high cell density, highly uniform;

Summary

In-situ Visualization: Strong tool/characterization method to

- identify unknown phenomena/mechanisms
- generate reliable experimental data

Modeling and Simulation

Simulation of Microcellular Injection Molding Process

Simulation of Microcellular Injection Molding Process

- **Topics**
  - **Introduction**
  - Core-back microcellular injection molding
  - Microcellular injection molding using chemical blowing agent
  - Effects of gas counter pressure

Flow Analysis for Microcellular Injection Molding

- **Mass Continuity equation**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

- **Momentum equation**

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho g$$

- **Energy equation**

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + \eta \dot{\gamma}^2 + \beta T \frac{Dp}{Dt}$$

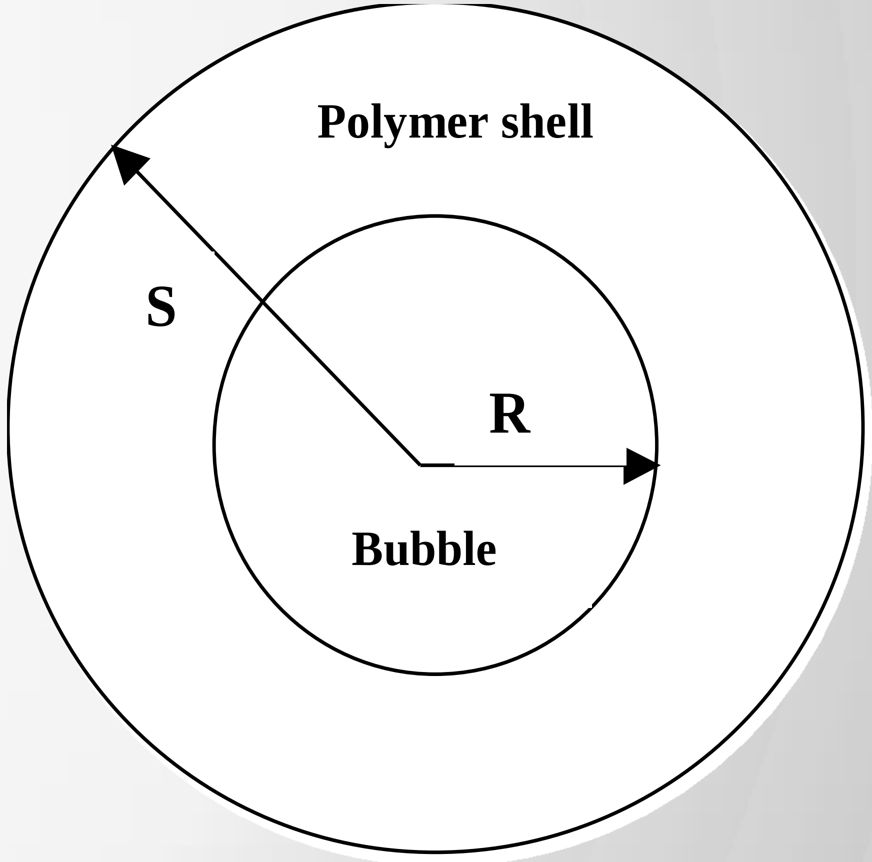
Bubble Growth Modeling

- **Expansion of cell due to**
  - **Hydrodynamic growth due to surrounding fluid**

$$4\eta \dot{R} / R = (P_g - P) - 2\sigma / R$$

  - **Diffusion of gas from envelope into bubble**

$$\frac{d}{dt}\left(\frac{p_g R^3}{R_g T}\right) = \frac{6\rho^2 D \kappa_h R_g T (p_{g0} - p_g)^2 R^4}{p_g R^3 - p_{g0} R_0^3}$$



P_g (pressure inside bubble), P (the melt pressure)

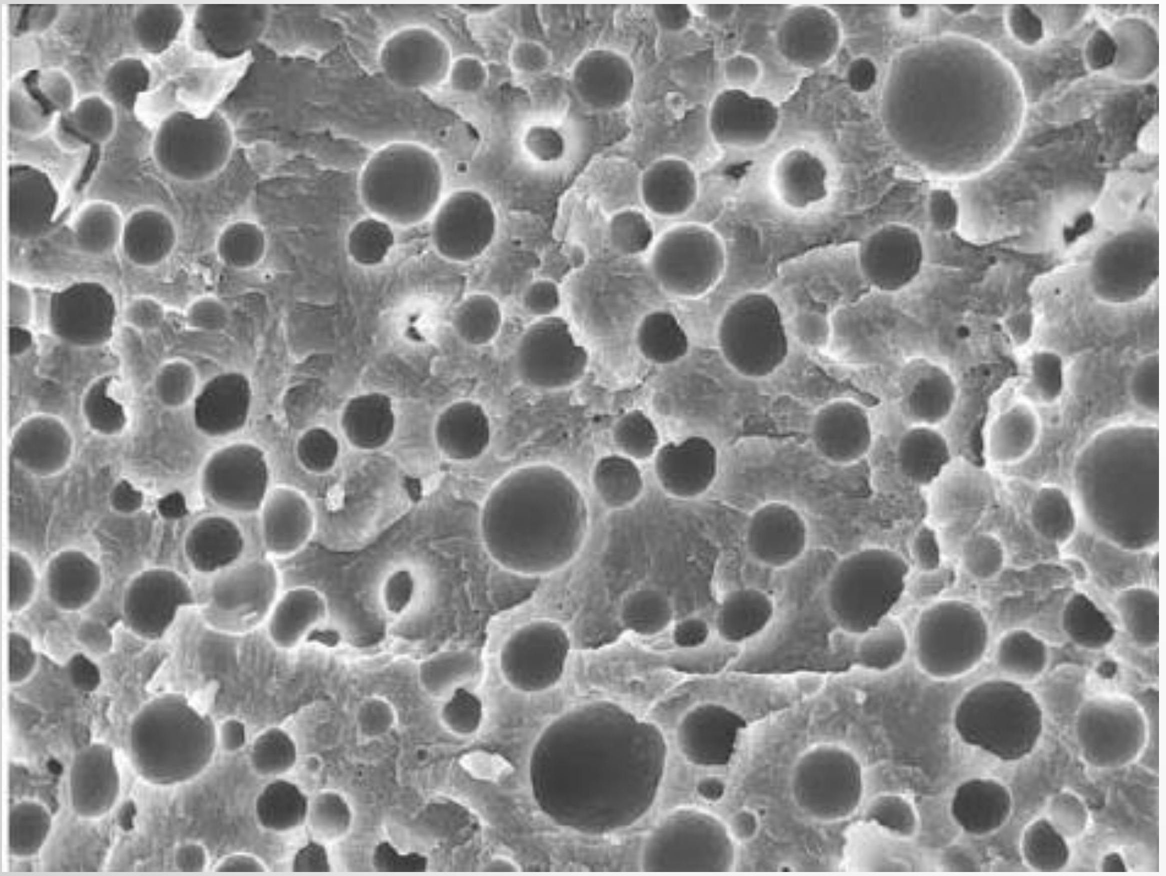
σ (surface tension), R_g (Universal gas constant)

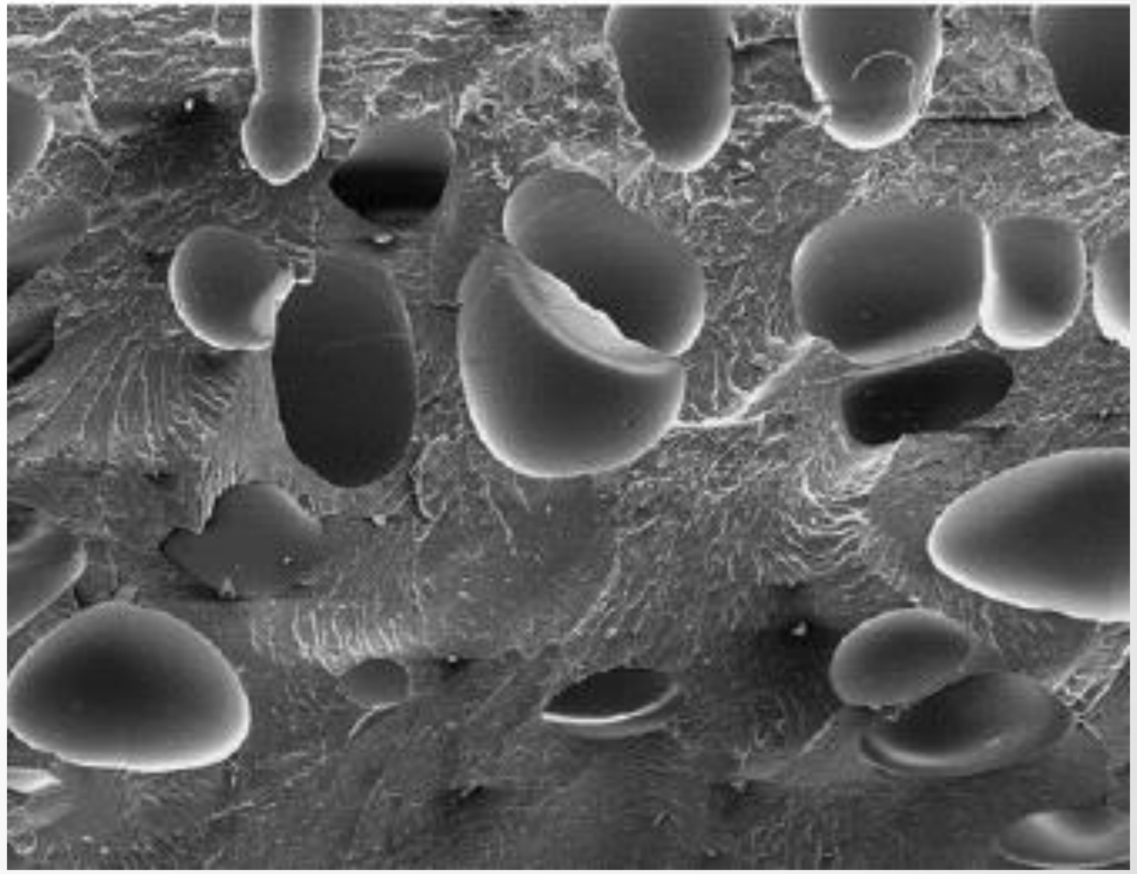
R (radius of the bubble), R_0 (initial radius of bubble)

(Amon and Denson (Polym. Eng. Sci 1984))

Bubble Nucleation Model

- Predict the bubble number density distribution in parts produced by microcellular injection molding
- Calculate the effects of effect of process conditions and material properties on bubble nucleation





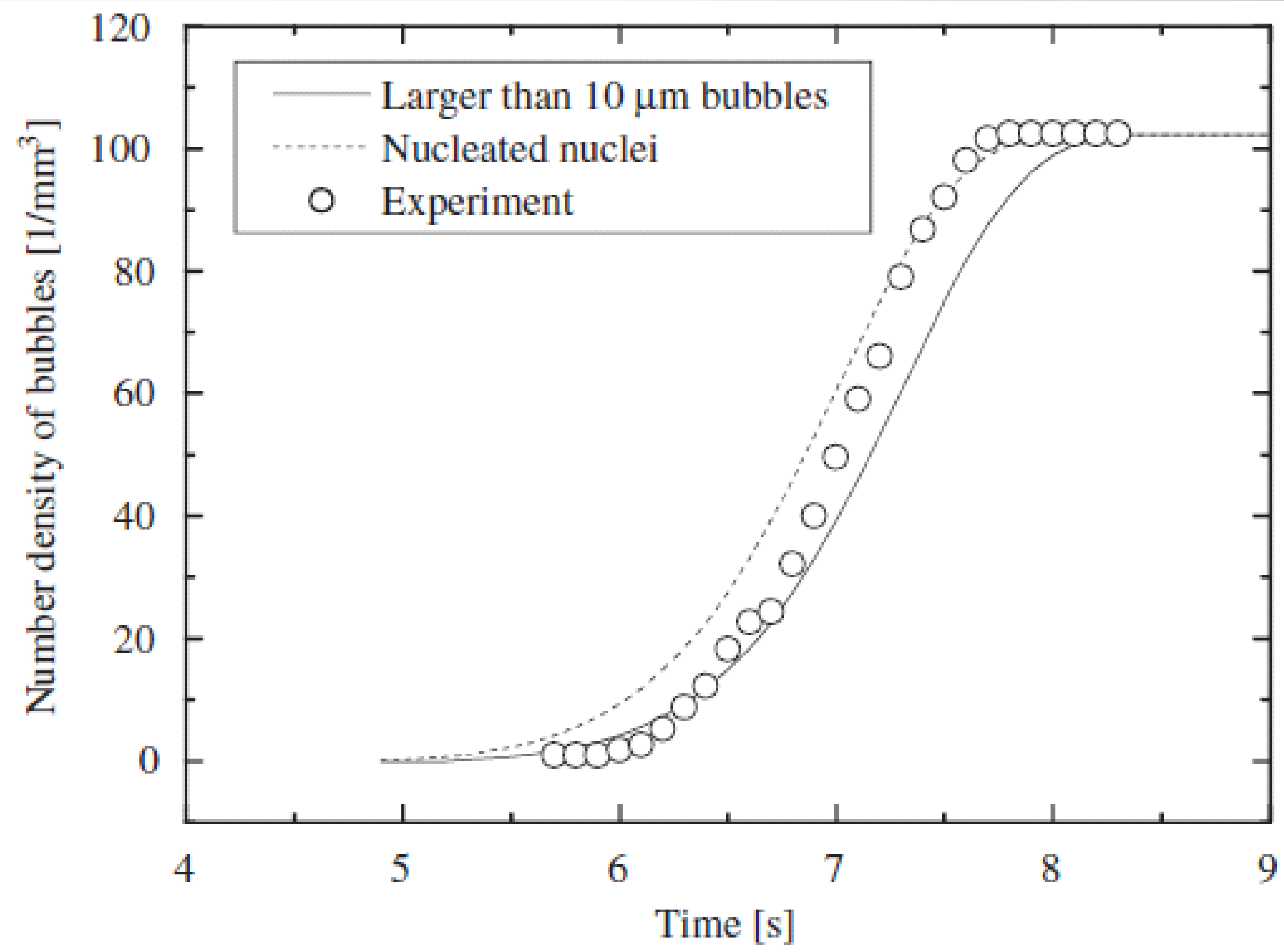
(Yuan & Turng (Polymer, 2005); Lee et al. (Polymer, 2011))

Fitted Nucleation Model

- **Fit the nucleation model to the actual nucleation density measurement data from the molding experiment**

$$J = F_1 N\left[\frac{2\sigma}{\pi m B}\right]^{\frac{1}{2}} exp\left[\frac{-16 F_2 \pi \sigma^3}{3kT[P_v - P_l]^2}\right]$$

- **F_1, F_2: Determined from fitting**

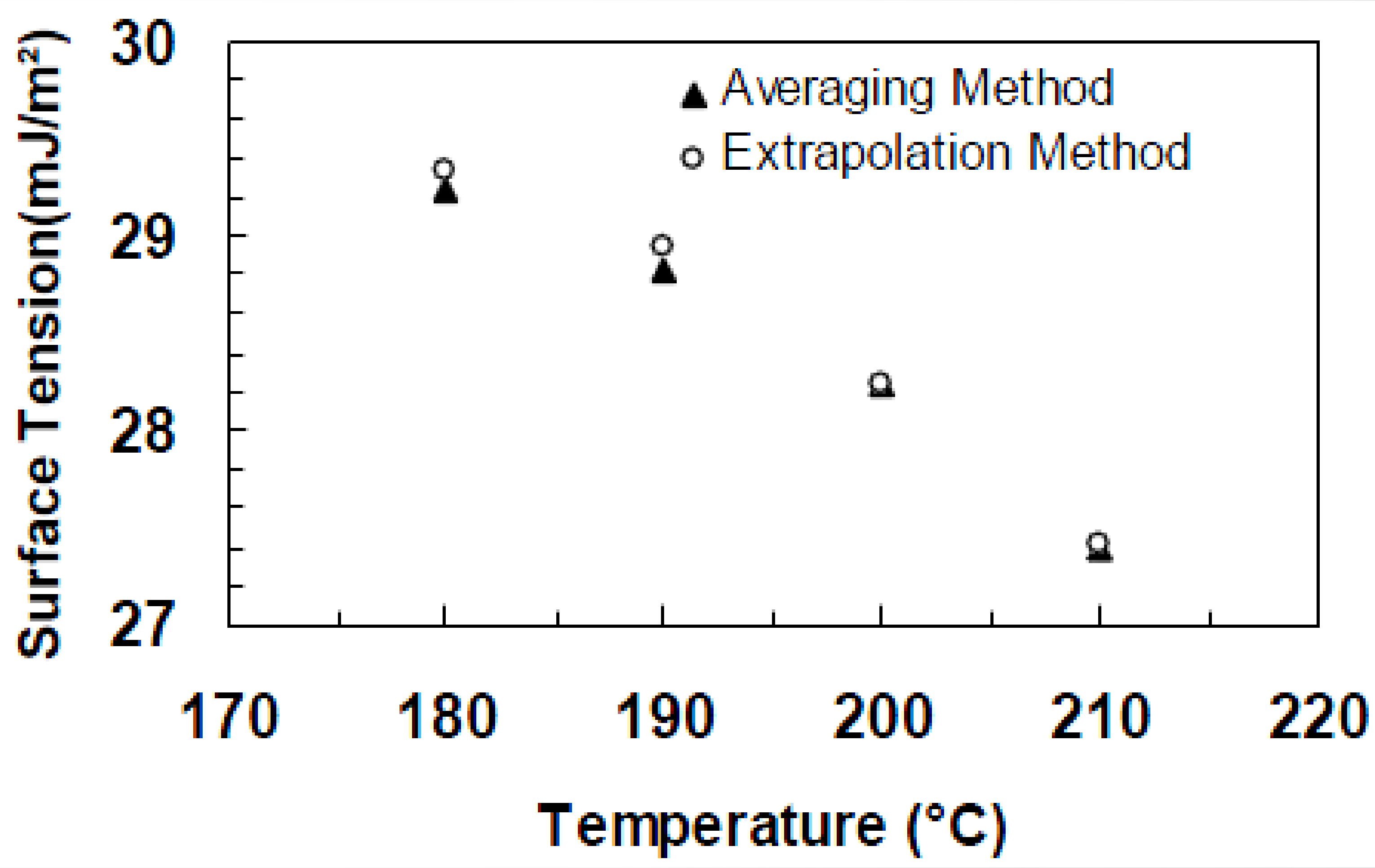


(K. Taki, Chem. Eng. Sci., 2008)

Material Data Model

- **Accurate material data is needed for accurate nucleation calculation**
- **Surface tension**

$$\sigma = \sigma_0(1 - \frac{T}{T_C})^{11/9} \quad \text{or} \quad \sigma = \sigma_0(\frac{\rho}{\rho_0})^4$$



- **Solubility**

$$\kappa_h = \kappa_{h0} exp(\frac{\kappa_{h1}}{T^2})$$

- **Diffusivity**

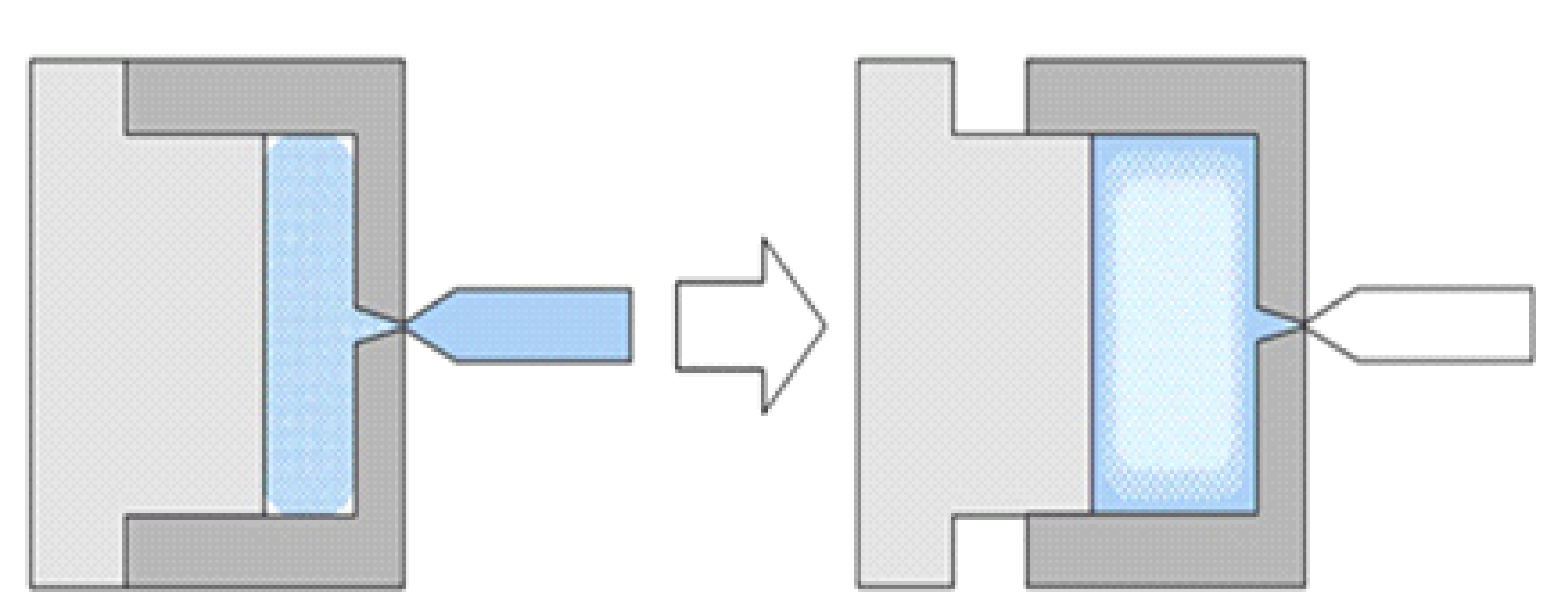
$$D = D_0 exp(\frac{D_1}{T})$$

Simulation of Microcellular Injection Molding Process

- **Topics**
  - Introduction
  - Core-back microcellular injection molding
  - Microcellular injection molding using chemical blowing agent
  - Effects of gas counter pressure

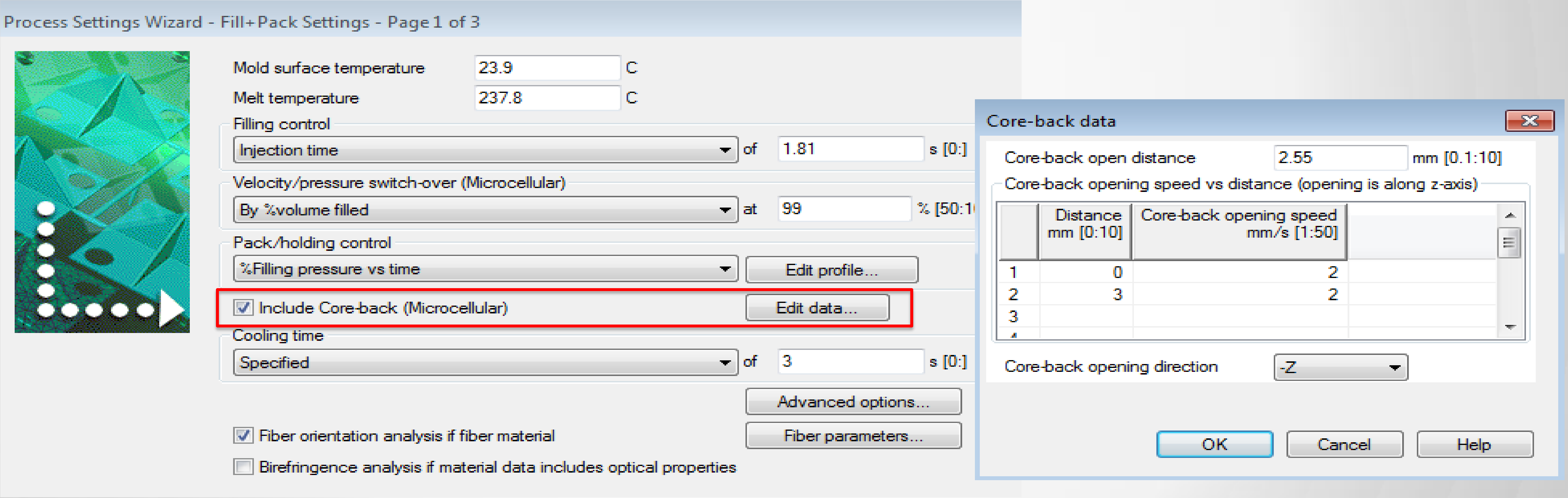
Core-back for Microcellular Injection Molding

- **Complete filling & packing before mold opening**
- **Mold opening: Bubble nucleation and growth with mold opening**
- **Advantages**
  - **Better surface quality**
  - **Higher part expansion ratio**



Core-back (Partial Mold Opening) for Microcellular Injection Molding

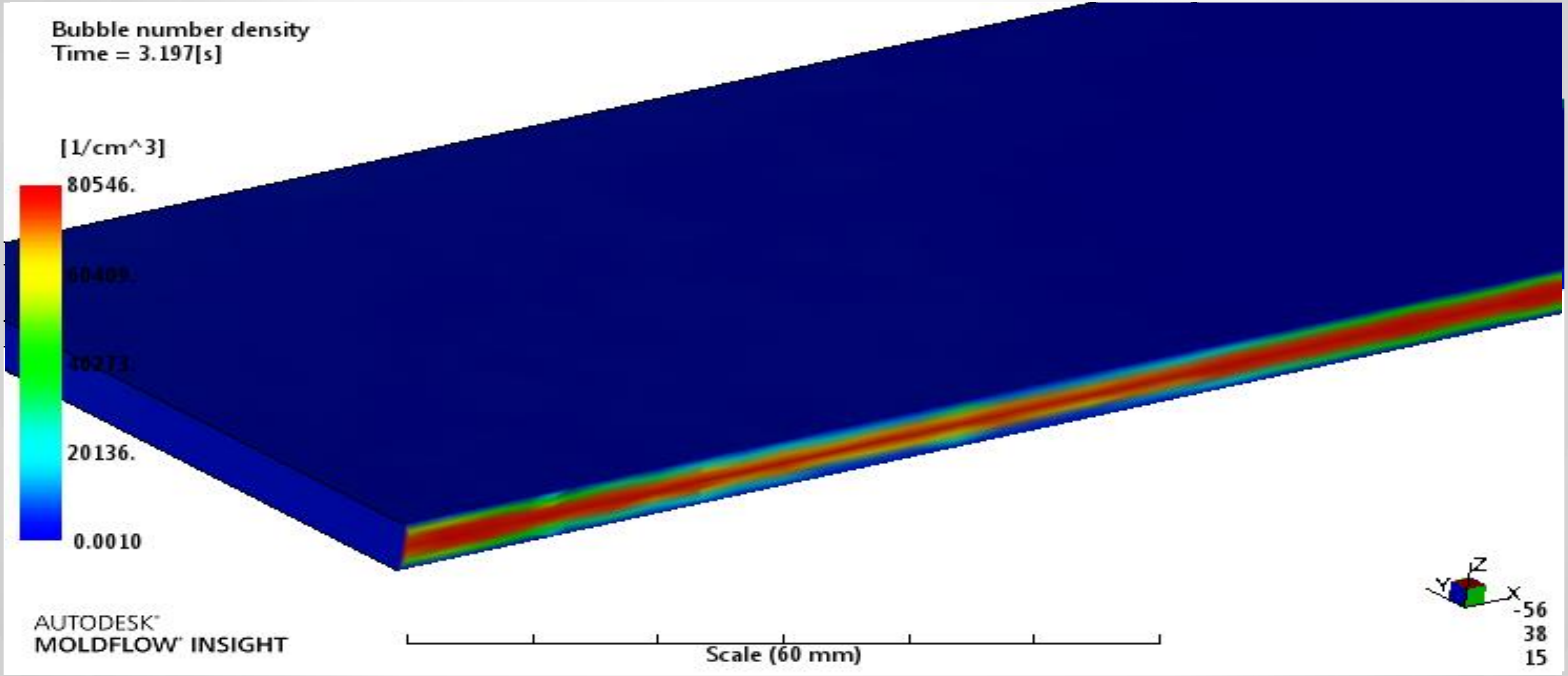
- Check “Include Core-back” option to run core-back analysis
- Specify distance, speed profile and direction of mold opening



Core-back (Partial Mold Opening) for Microcellular Injection Molding

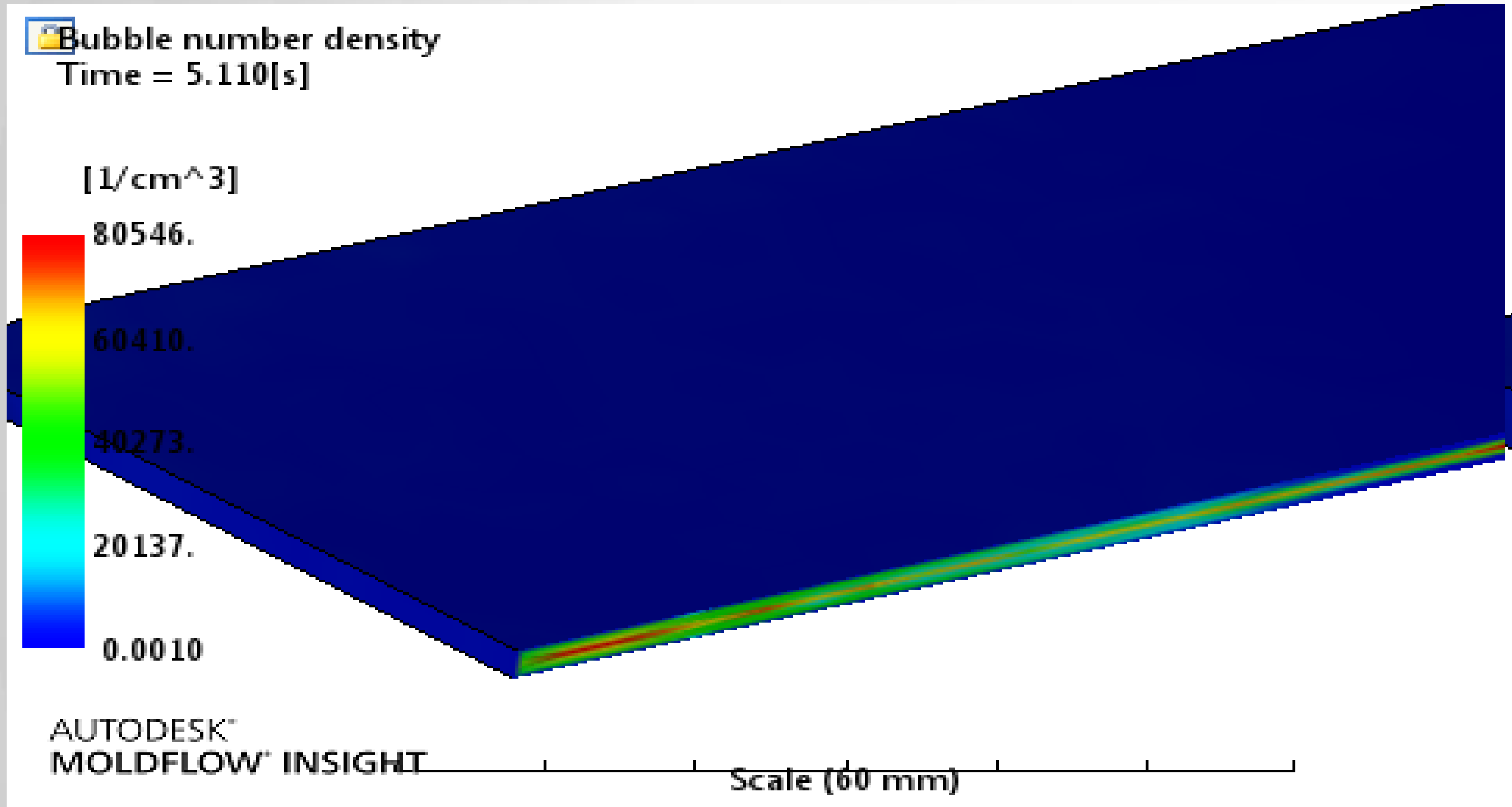
- **Available for analysis sequences that include "Fill+Pack"**
  - **Not available for "Fill" only**
- **Core-back occurs at the end of the packing phase**
- **Model the elements to be opened using "Compression (3D)" element**
- **Negative values for press displacement or press speed -> Mold opening**

Case 1: Bubble Number Density Result

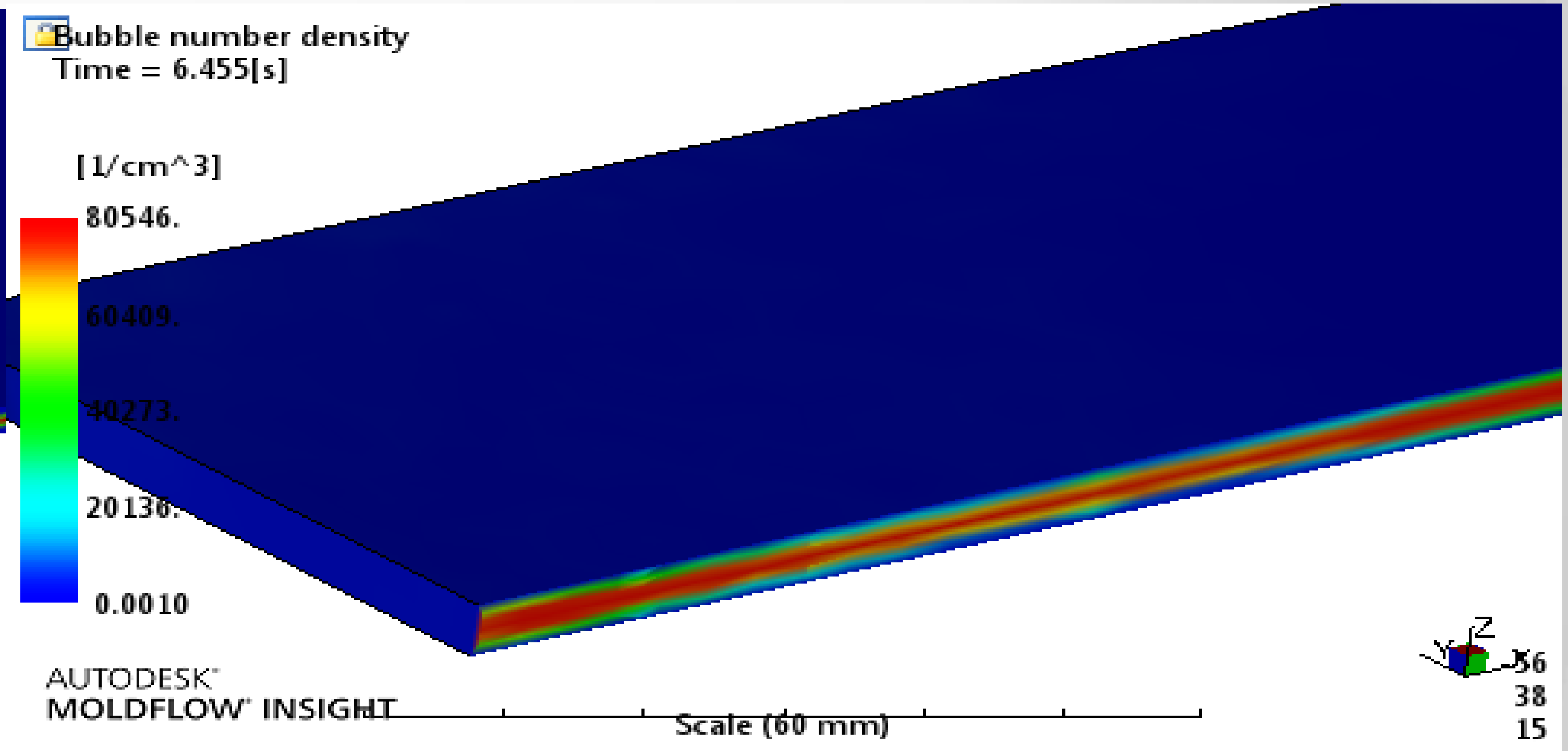


More Bubbles with Core-Back

No Core-Back



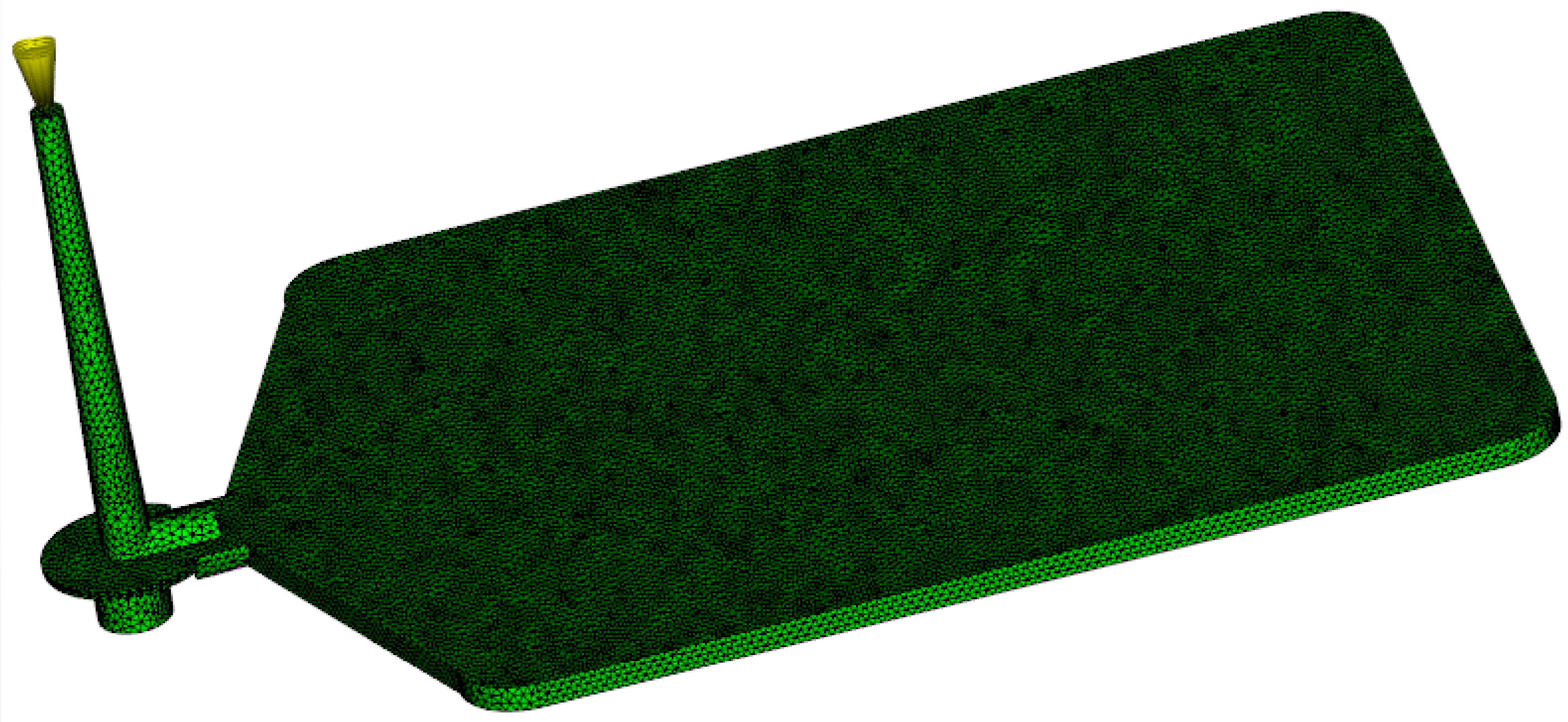
With Core-Back



*Core-back feature only for 3D at present

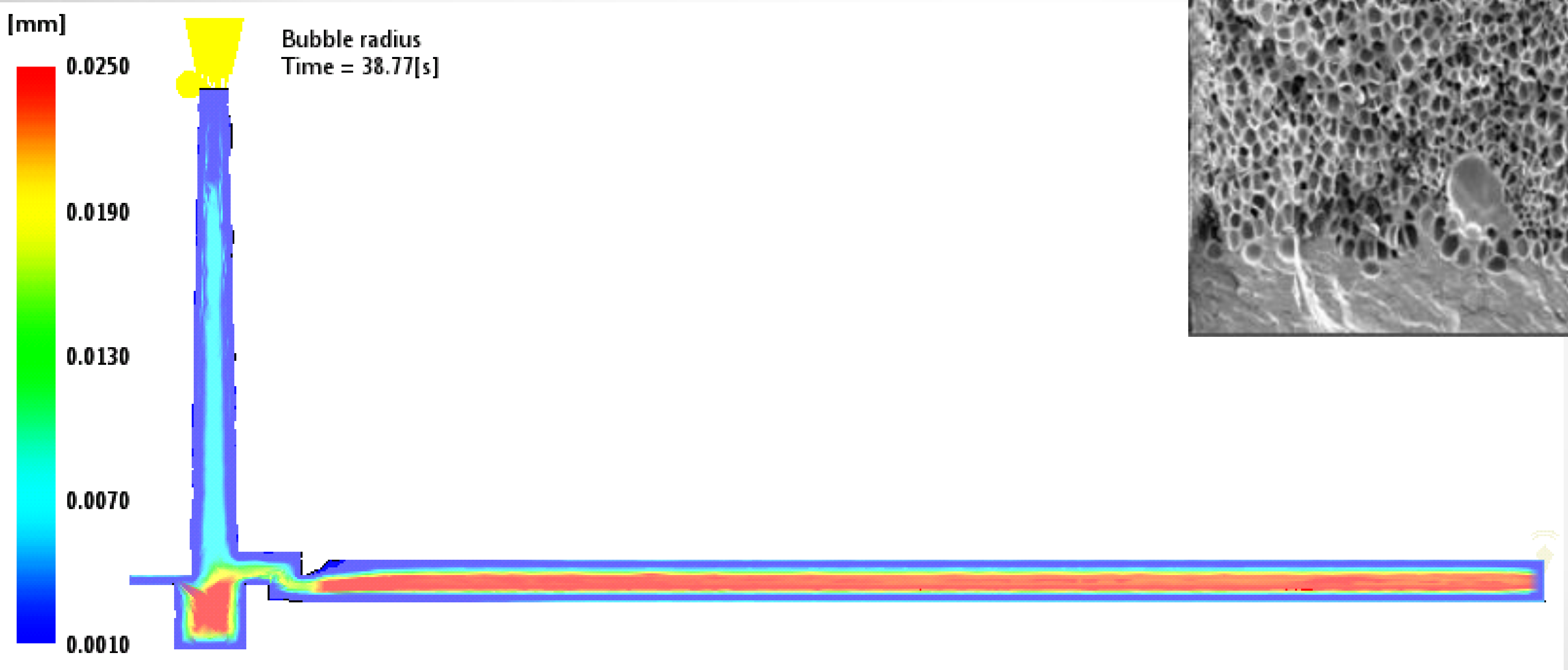
Case 2: Plate

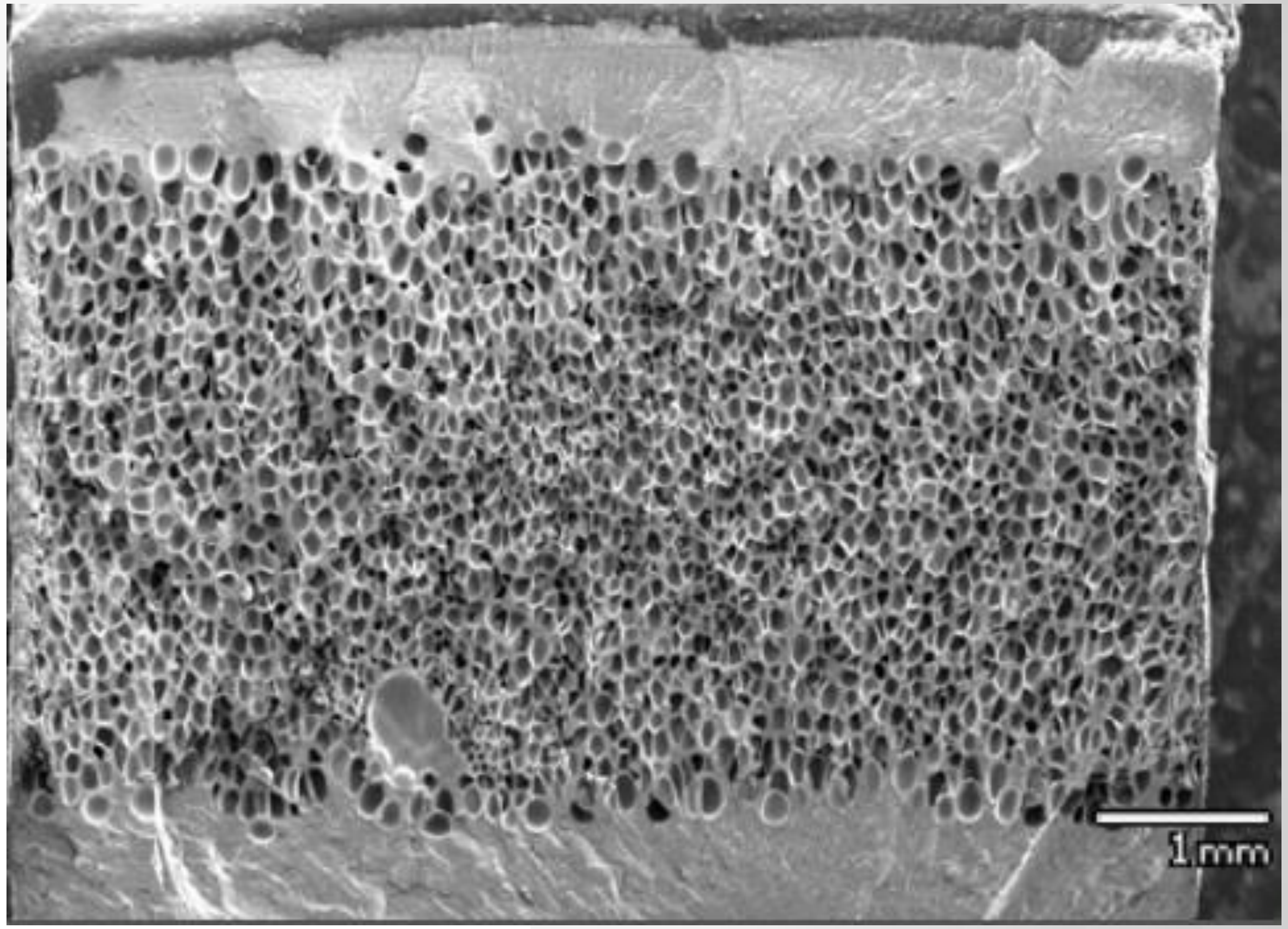
- **Resin: PS**
- **Foaming gas: CO_2 (5% by weight)**
- **Plate initial thickness: 3.2 mm**
- **Packing: 6 or 20 MPa for 8 sec**
- **Open distance: 2 mm**



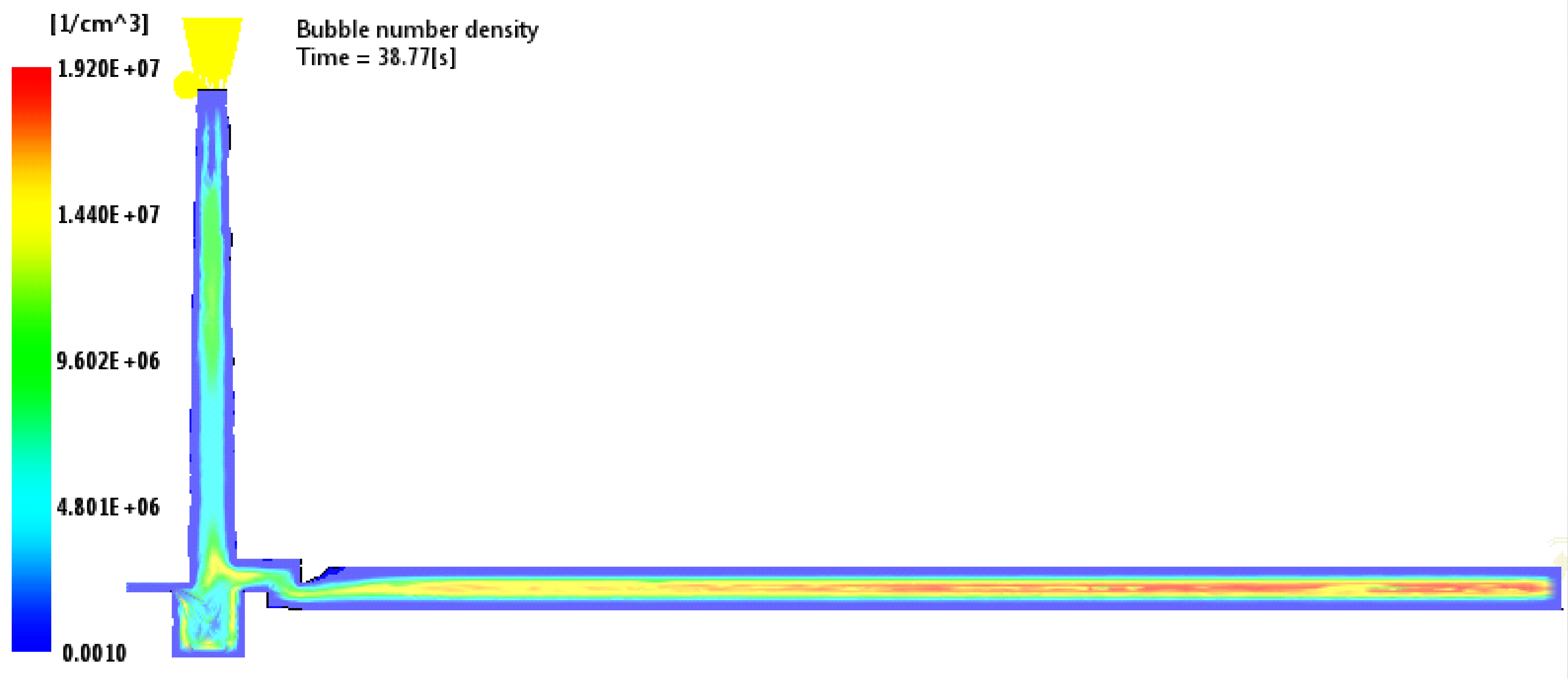
Case 2: Calculated Bubble Radius

- **Experiment: Univ. Toronto**





Case 2: Calculated Bubble Number density



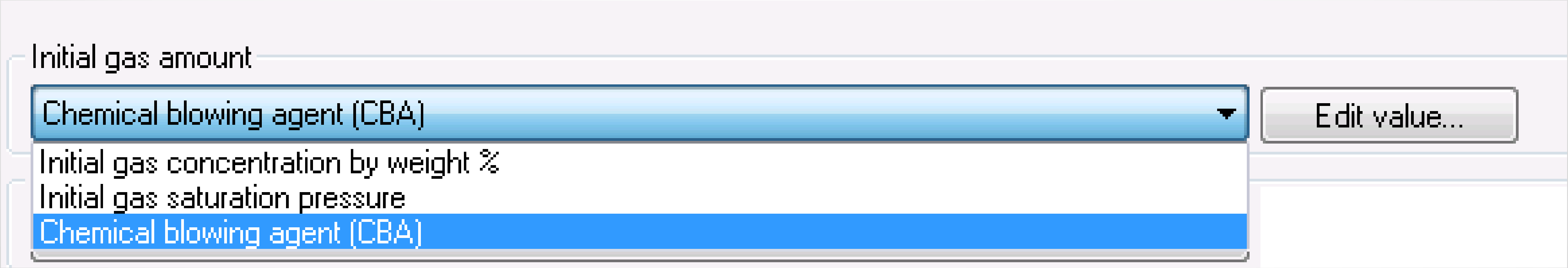
Simulation of Microcellular Injection Molding Process

- **Topics**
  - Introduction
  - Core-back microcellular injection molding
  - **Microcellular injection molding using chemical blowing agent**
  - Effects of gas counter pressure

Microcellular Injection Molding by Chemical Blowing Agent

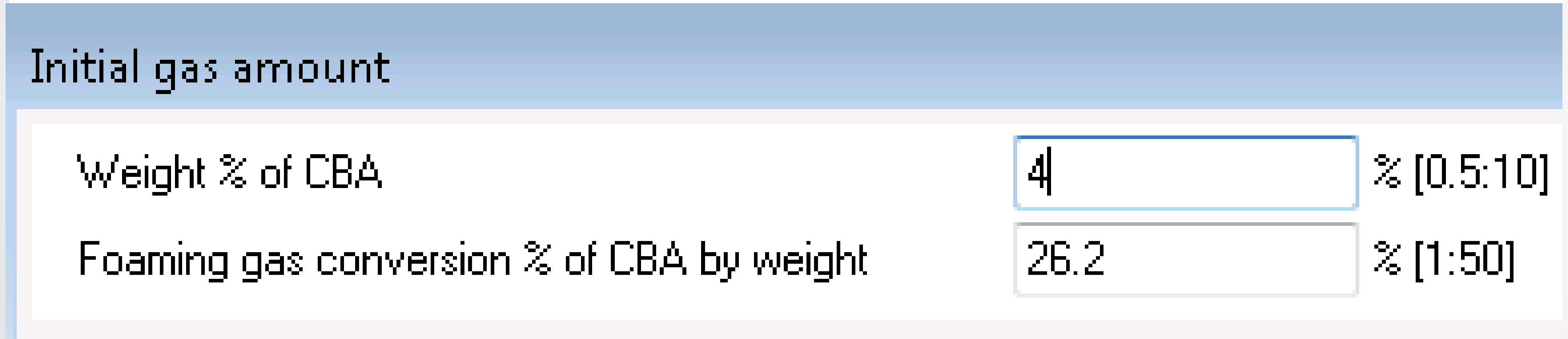
- Chemical reaction in the barrel produces foaming gas in solution
  - Assume reaction is complete in the barrel

- Choose “Chemical blowing agent” for “Initial gas amount” option



Input Data

- **Weight % of CBA: Weight % of CBA in the resin**
- **Foaming gas conversion % of CBA by Weight: The % mass of foaming gas generated per unit mass of CBA**

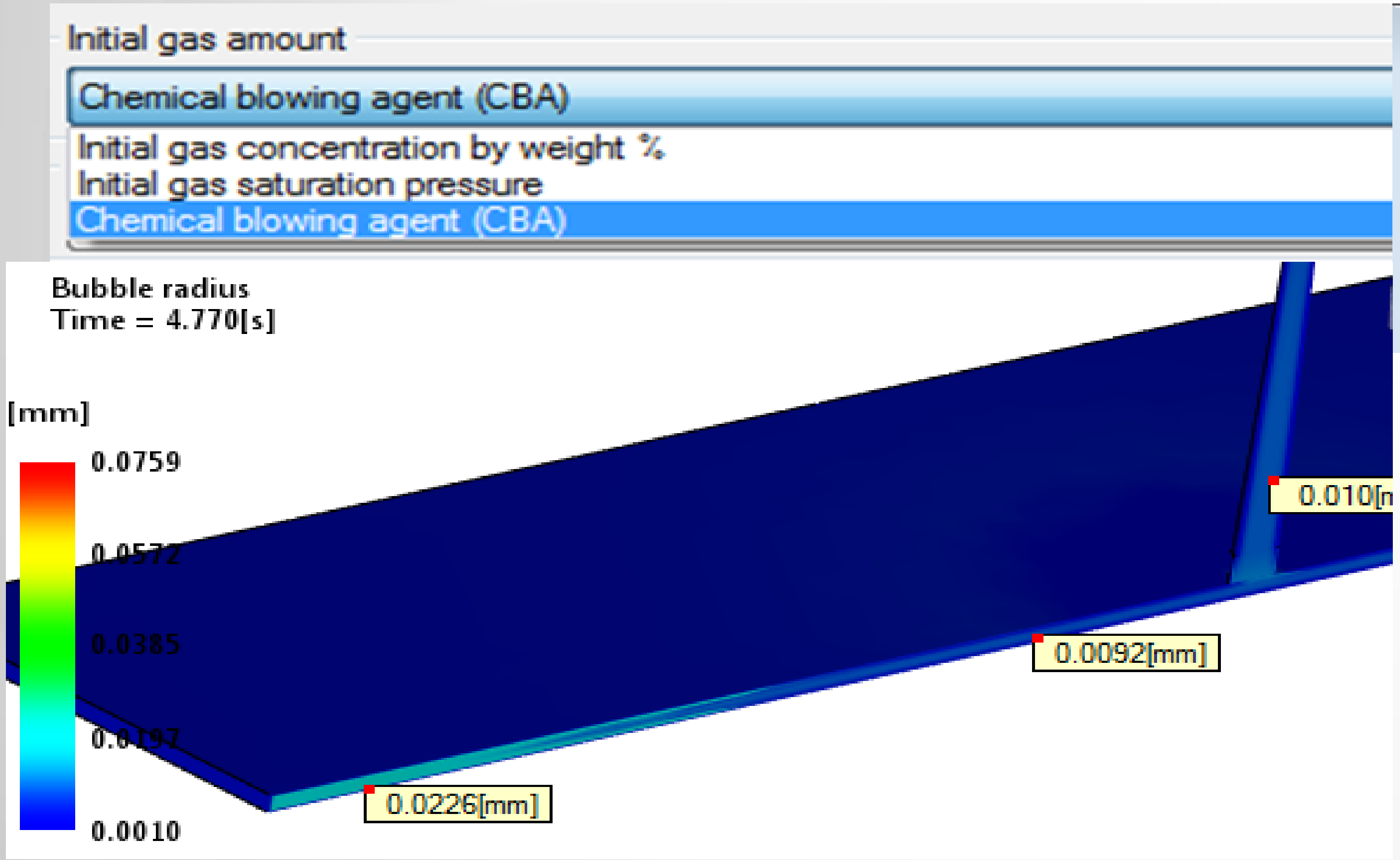


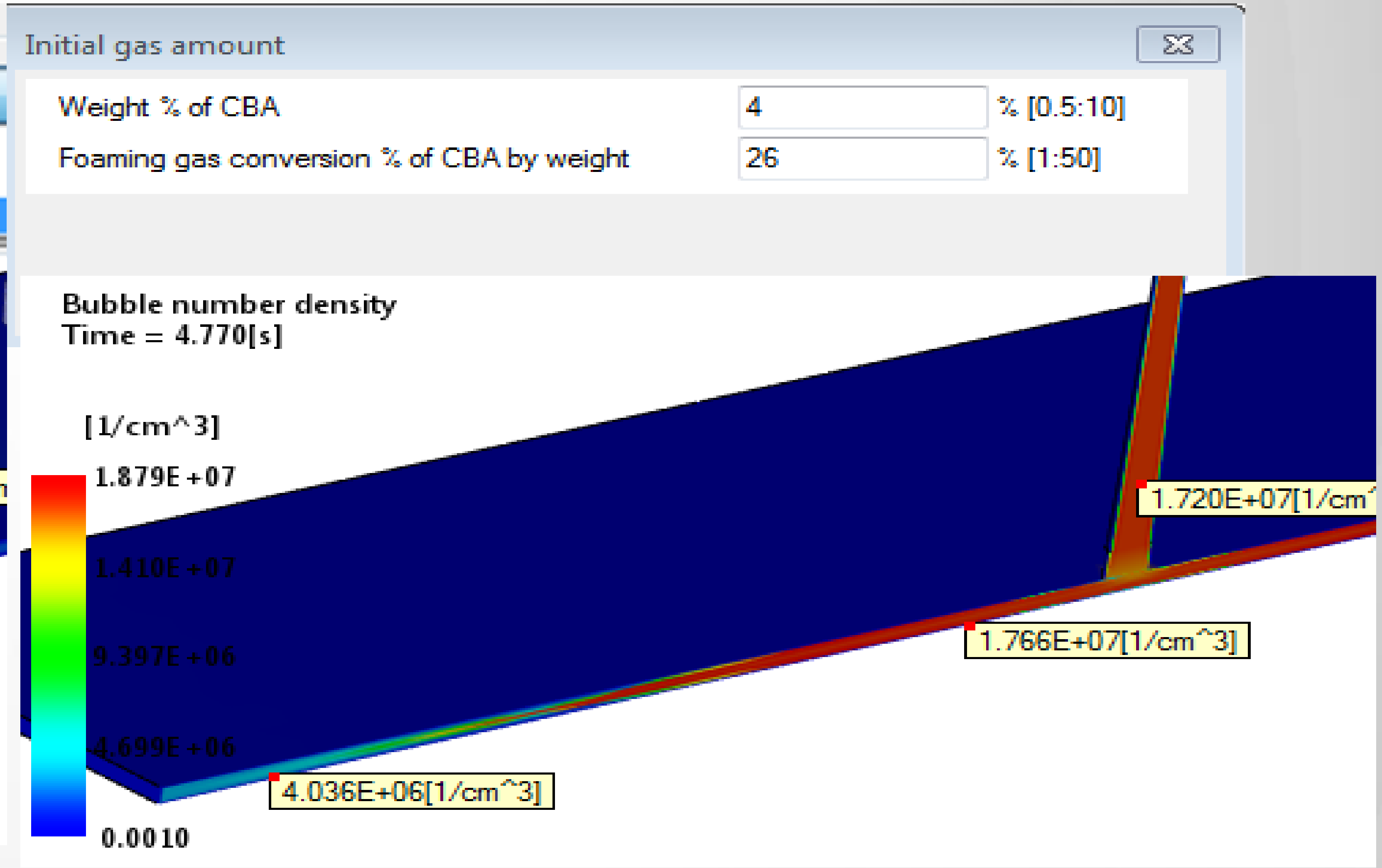
An Example of CBA

- $NaHCO_3$ -> O.5 Na_2CO_3 + 0.5 CO_2 + 0.5 H_2O
- Calculation of “Foaming gas conversion % of CBA by Weight”
  - Molecular weight of $NaHCO_3$ = 84
  - Molecular weight of CO_2 = 44
  - Foaming gas conversion % of CBA by Weight
    - = 100 * (Molecular weight of 0.5 * CO_2) / (Molecular weight of $NaHCO_3$)
    - = 100 * (0.5*44)/84 = 26.2%

Foaming by Chemical Blowing Agent

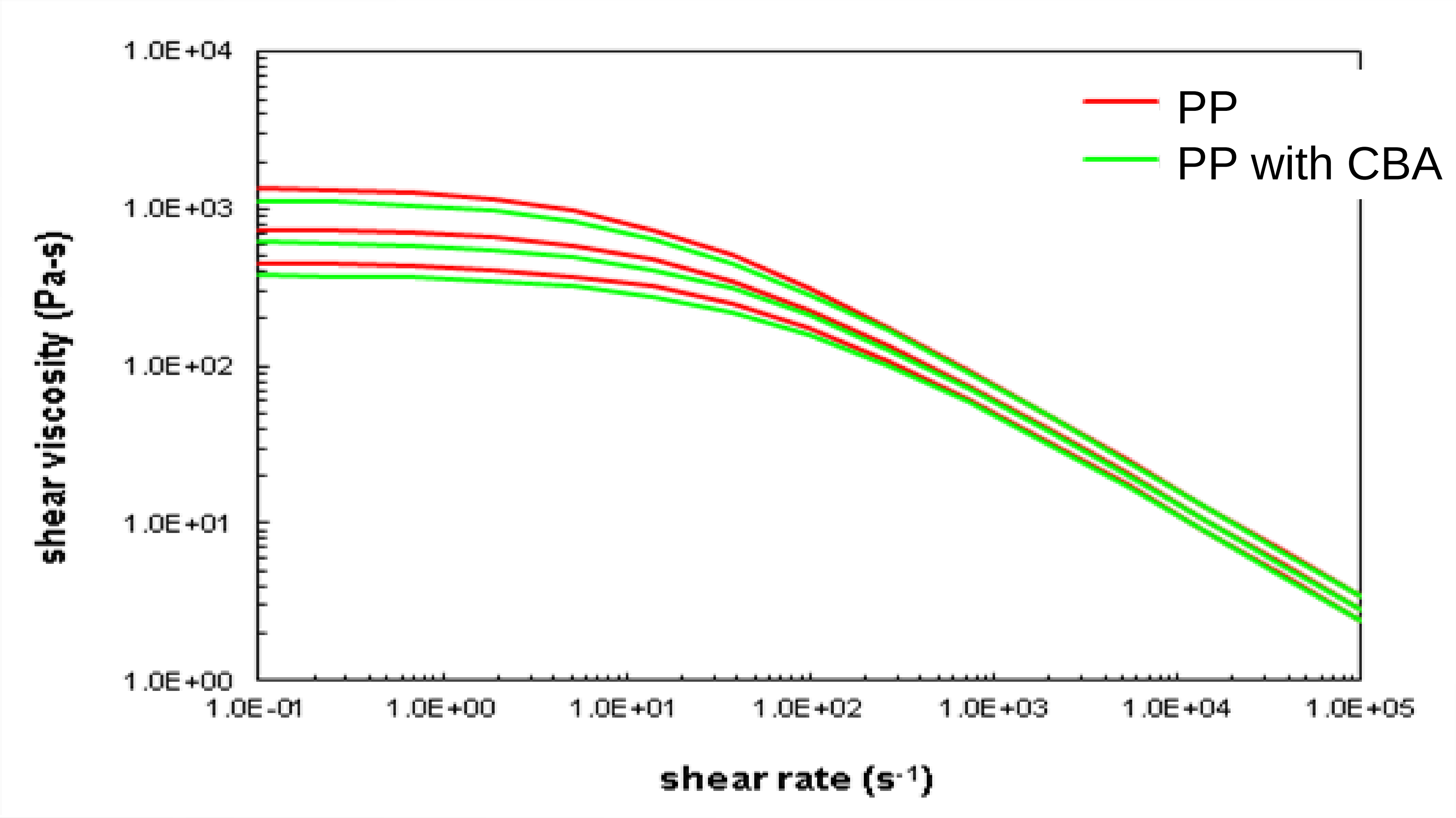
- Chemical reaction in the barrel produces CO_2 in solution
  - Assume reaction is fully complete in the barrel





Foaming by Chemical Blowing Agent

- **Research Project: Tested viscosity for a PP with 4 wt% Chemical Blowing Agent (CBA)**
  - **Injection Molding Rheometer with shutoff valve**

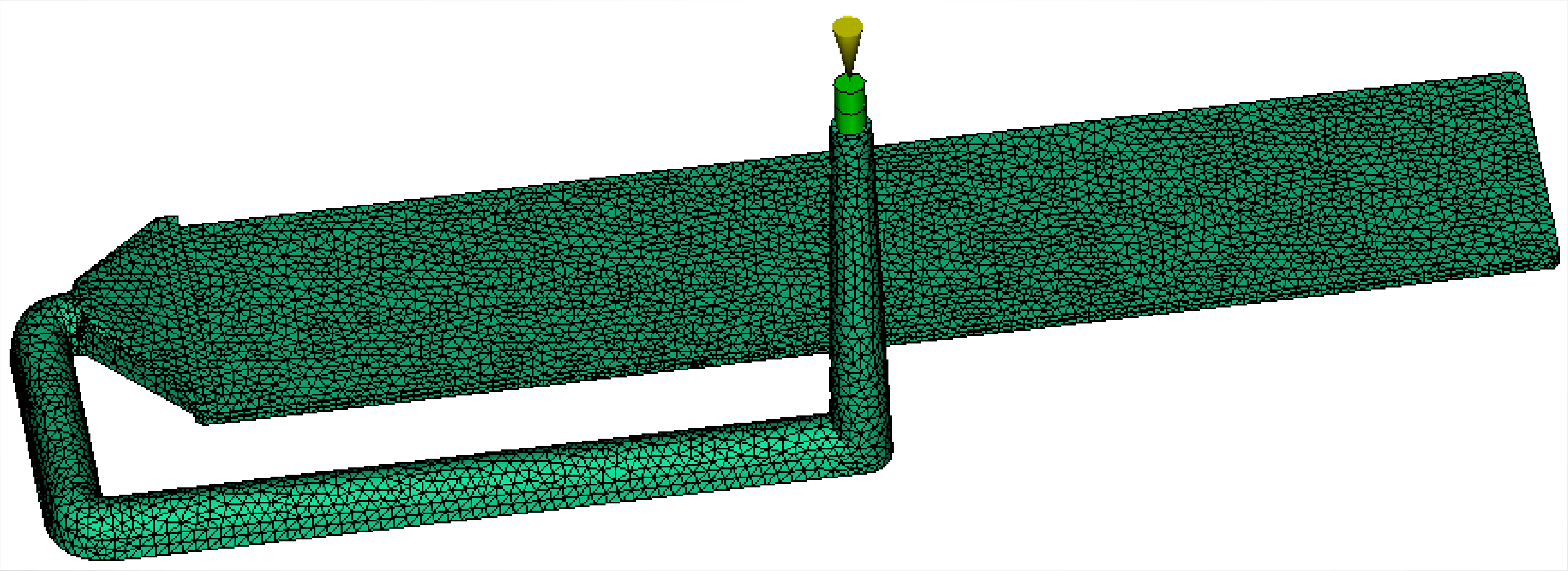


Gas content: 1wt%
Only a small effect on shear viscosity

$$\eta = \eta_r (1-\phi)^{v_1} \exp(v_2 c + v_3 c^2)$$

Tag-Die Case

- **Resin: PP**
- **CBA: $NaHCO_3$**
- **CBA weight%: 4**
- **Initial melt temperature: 225°C**
- **Mold temperature: 50°C**



Kinetics of CBA Reaction

- **Thermal decomposition of $NaHCO_3$:**

  $NaHCO_3$ -> O.5 Na_2CO_3 + 0.5 CO_2 + 0.5 H_2O

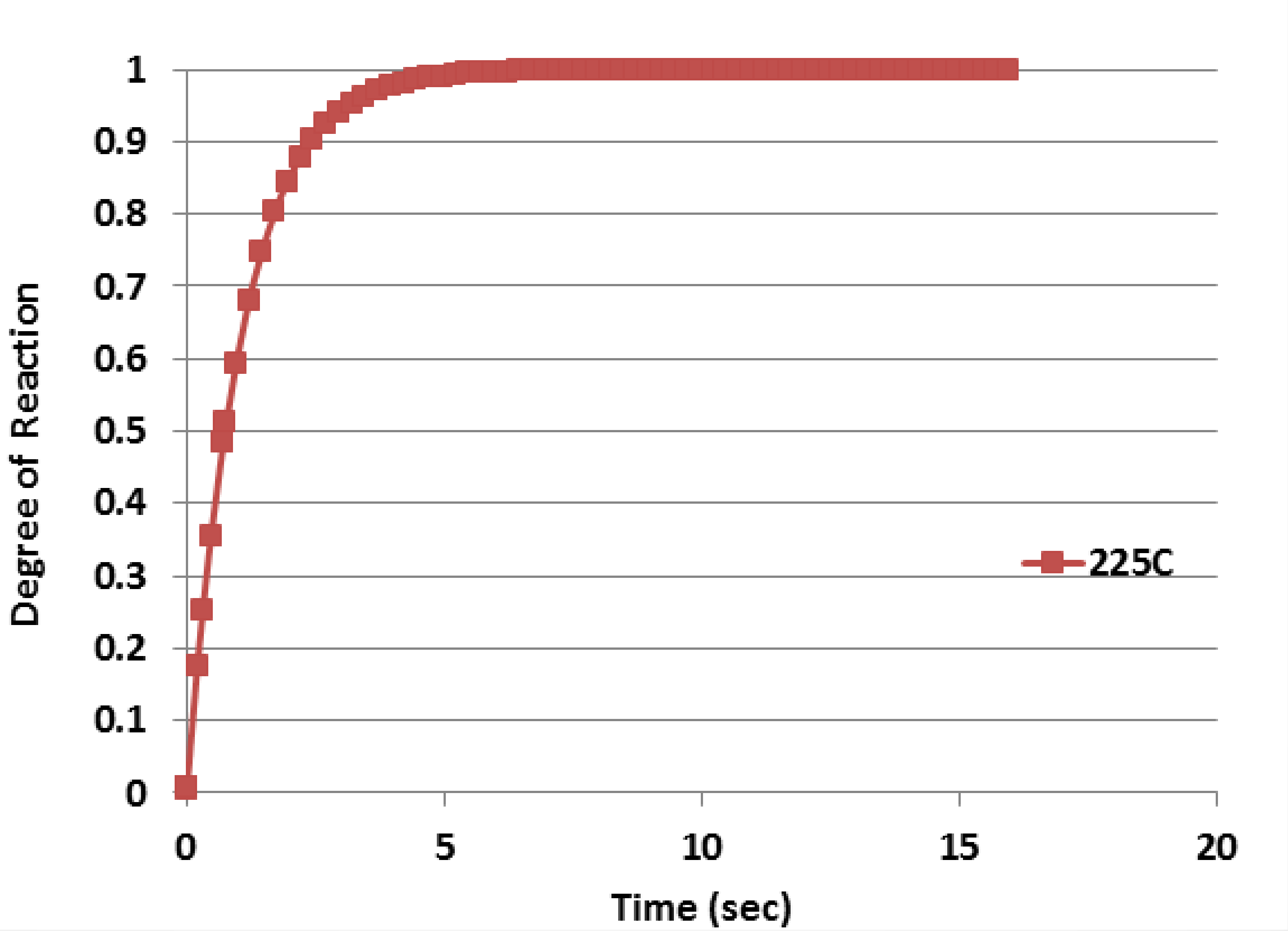
- **Degree of reaction calculation**

  $$d\alpha/dt = K_0 \exp(-E/R_gT)(1 - \alpha)$$

  Where α: degree of reaction
  R_g: Gas constant
  K_0, E: Constants

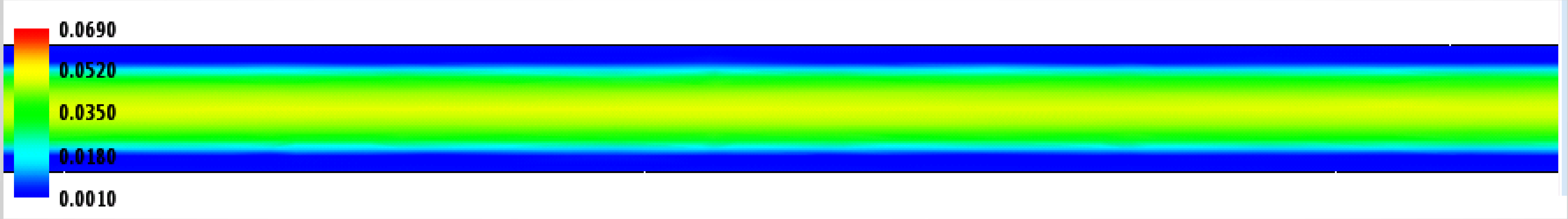
Kinetics of CBA Reaction

- **Time – degree reaction of $NaHCO_3$ thermal decomposition at 225C**
- **It confirms that the reaction completes in the barrel within the residence time**

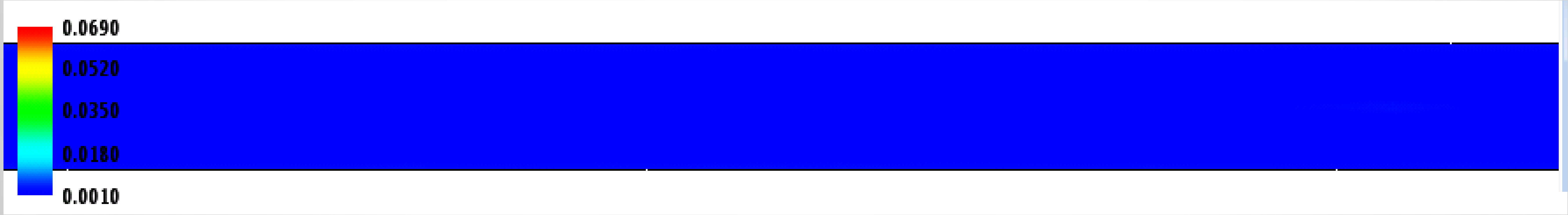


Tag-Die Case: Bubble Radius Results

- No packing



- Packing (24 MPa for 15 sec)



Simulation of Microcellular Injection Molding Process

- **Topics**
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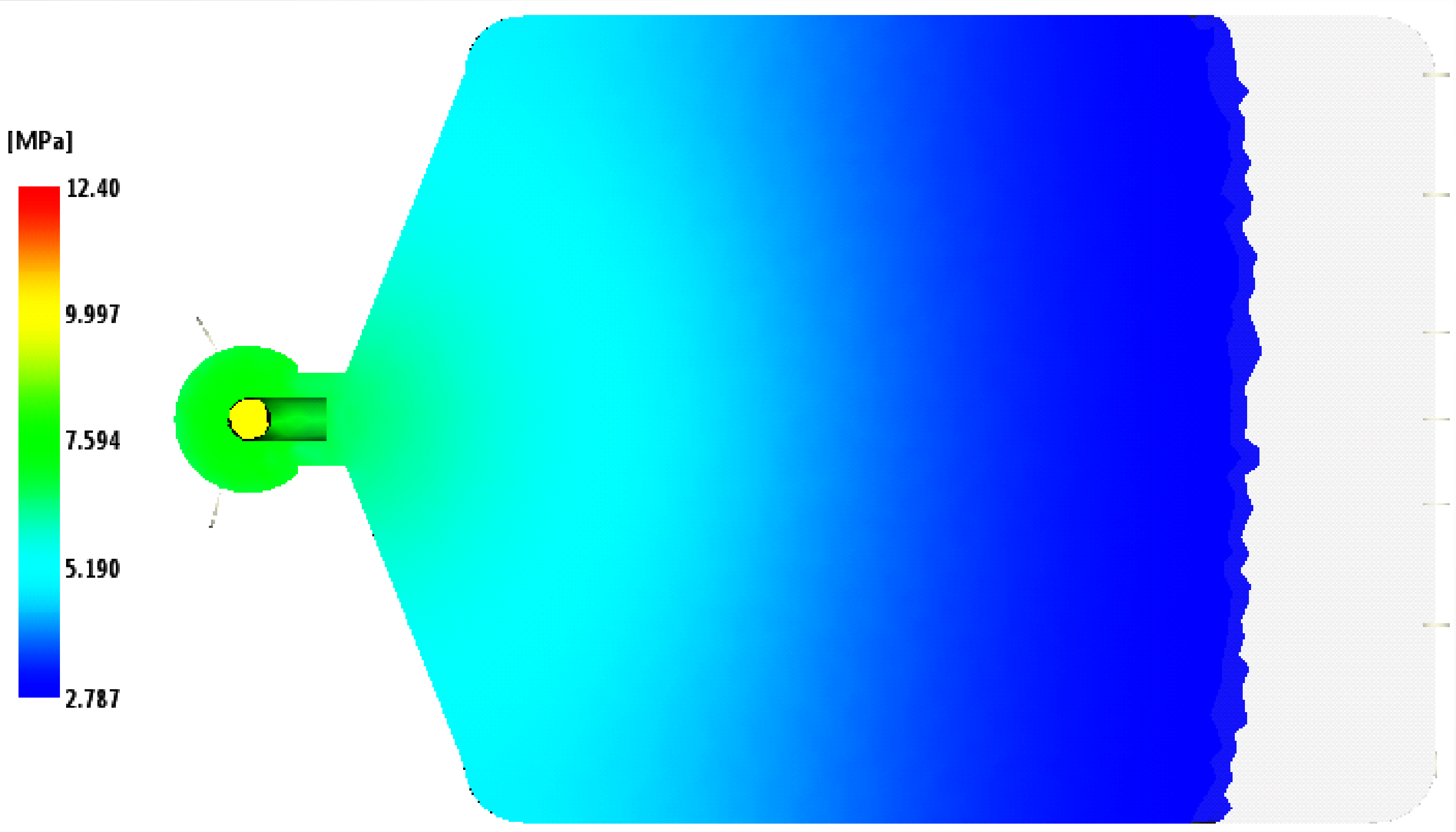
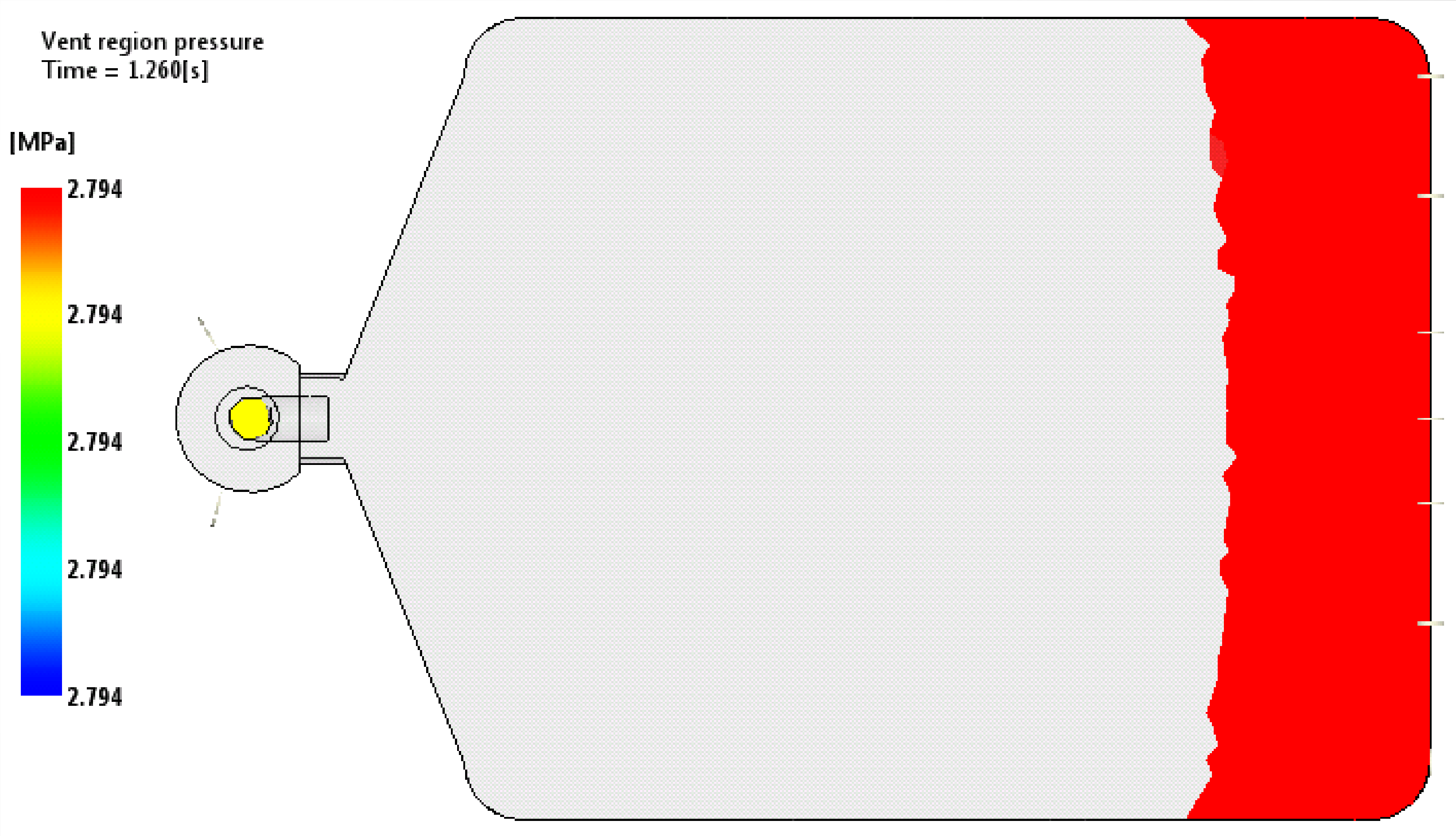
Microcellular Injection Molding with Gas Counter Pressure

- **Use venting analysis to simulate gas counter pressure**
- **The high pressure at the melt front will suppress bubble nucleation / growth during filling**

Gas Counter Pressure: Example

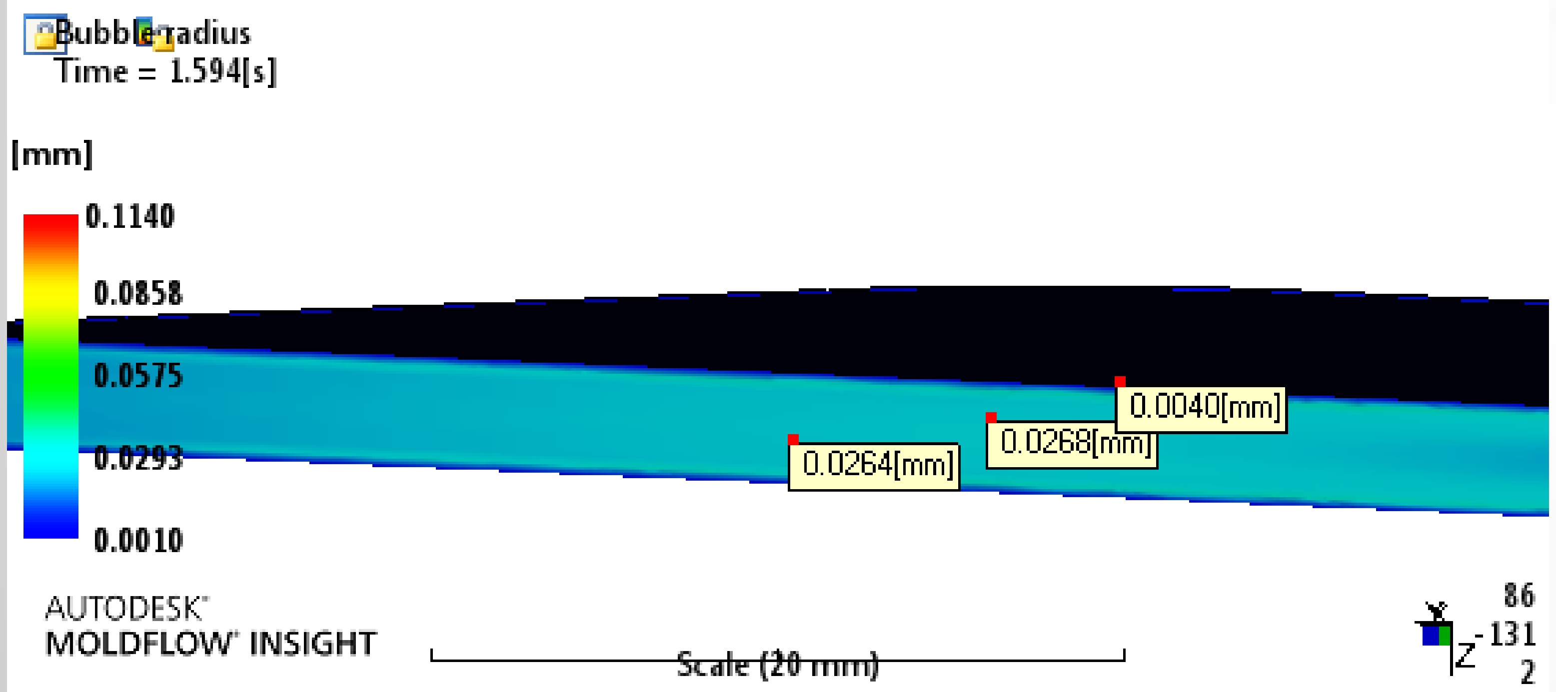
- **Pressure and vent region pressure plot for the case with gas counter pressure (about 2.8 MPa)**

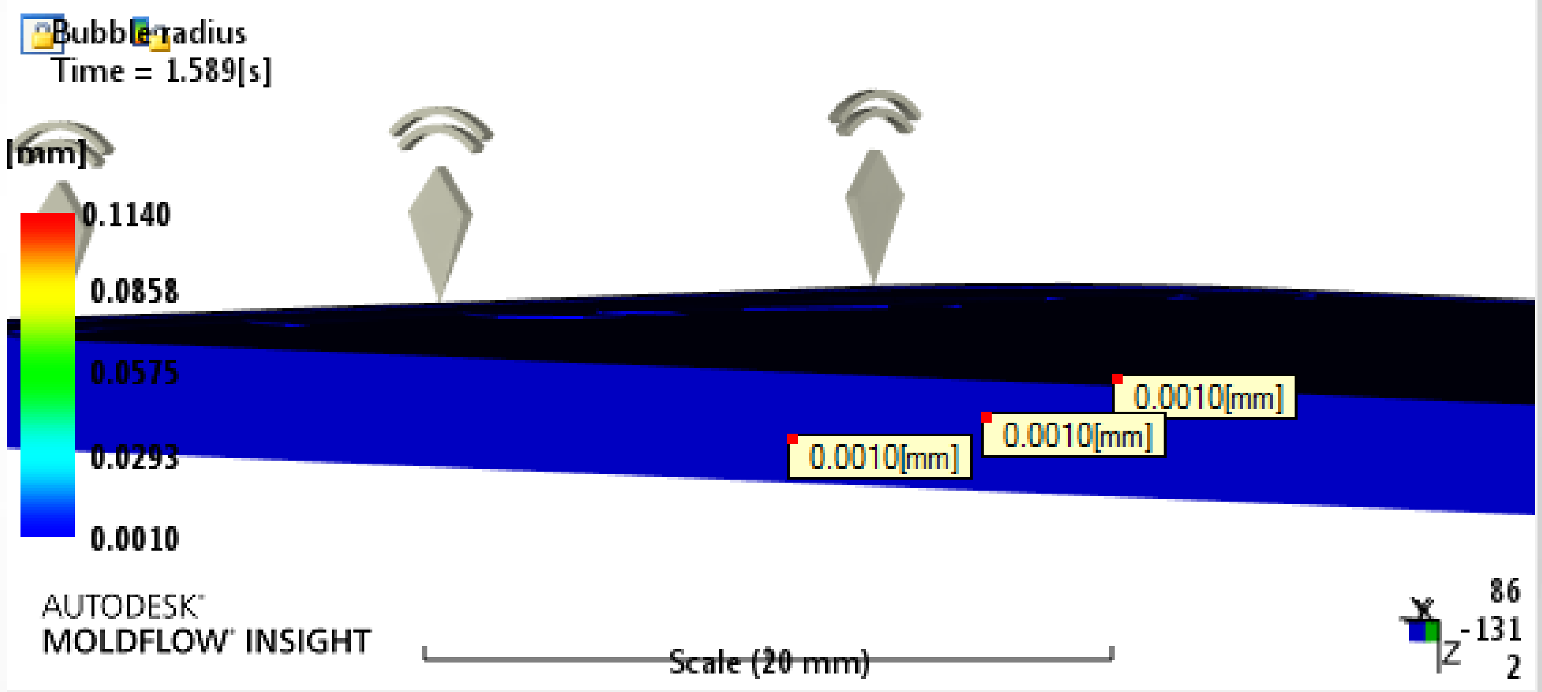




Bubble Radius: Without and With Gas Counter Pressure

- **Almost no bubble growth during filling with gas counter pressure (initial bubble radius = 0.001 mm)**

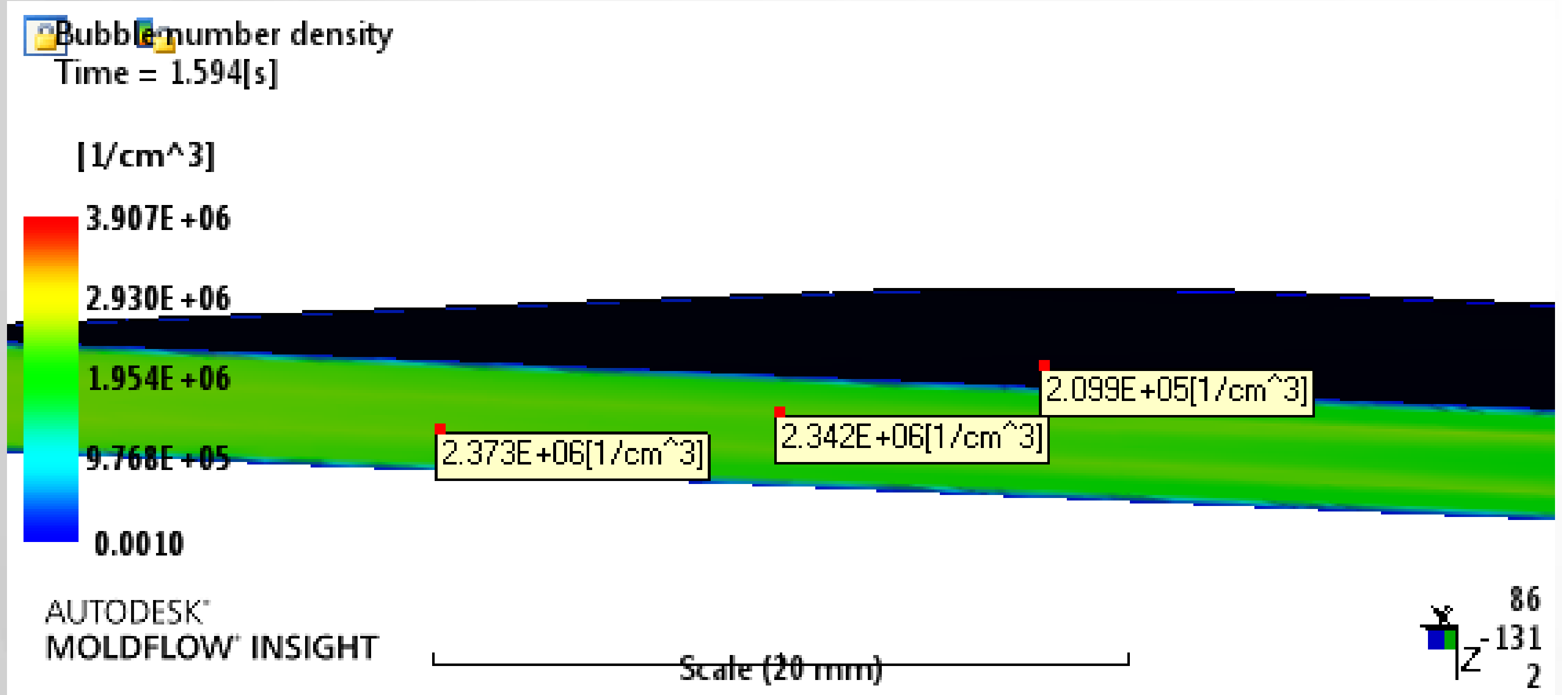


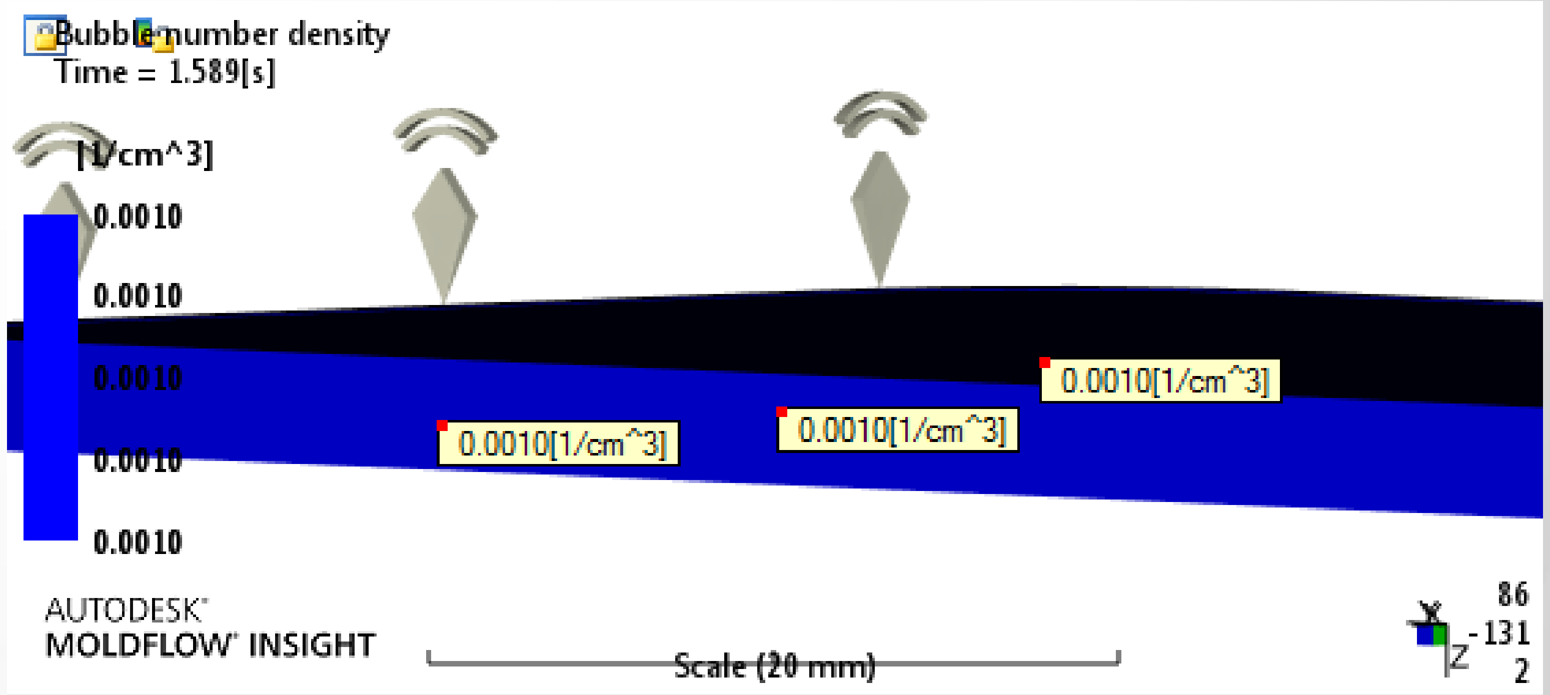


Without gas counter pressure **With gas counter pressure**

Bubble Number Density: Without and With Gas Counter Pressure

- **Almost no bubble nucleation during filling with gas counter pressure (initial bubble number density = 0.001 /cm³)**





Without gas counter pressure **With gas counter pressure**

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Thank you very much !