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The Application of Through Vial Impedance Spectroscopy (TVIS) for Process Parameter Determination in Freeze-Drying Method Development

PDA Europe
Pharmaceutical Freeze Drying Technology
Strasbourg, 27 – 28 September 2016

Outline

- Introduction of Through Vial Impedance Spectroscopy (TVIS) Technology

- TVIS Applications
  - K_V Determination
  - R_P Determination
  - Other Applications
    - Ice nucleation,
    - Glass transition,
    - Eutectic Crystallization
    - Collapse

Through Vial Impedance Spectroscopy (TVIS)

Through Vial Impedance Spectroscopy (TVIS)

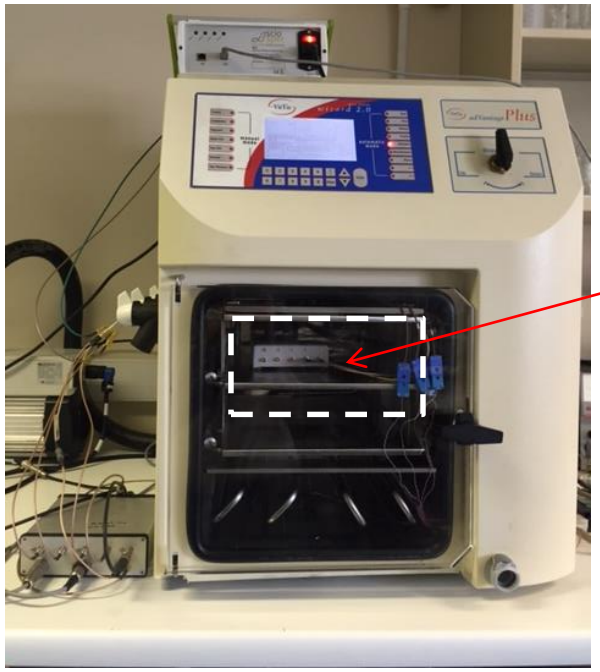
- Impedance measurements across a vial rather than within the vial
- Hence "**Through Vial Impedance Spectroscopy**"
- "Non-product invasive"
- Stoppering possible
- Non-perturbing to the packing of vials

- On going TVIS development for multiple scales:
  - Product Development (Microplate, Micro-vial, or Single vial)
  - Mini-Pilot (Small population clusters of vials)
  - Scale up to Batch (Large population cluster of vials)

- Mesoscale accessible by assessing the temperature dependence of impedance

Through Vial Impedance Spectroscopy (TVIS)

Freeze Dryer and TVIS System



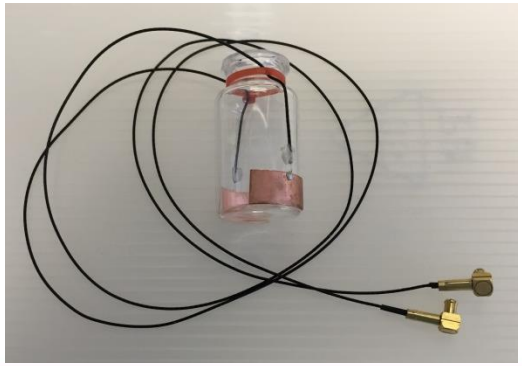
Virtis Advantage Pro Freeze Dryer

Junction box

Pass-through

TVIS System

Impedance test vial

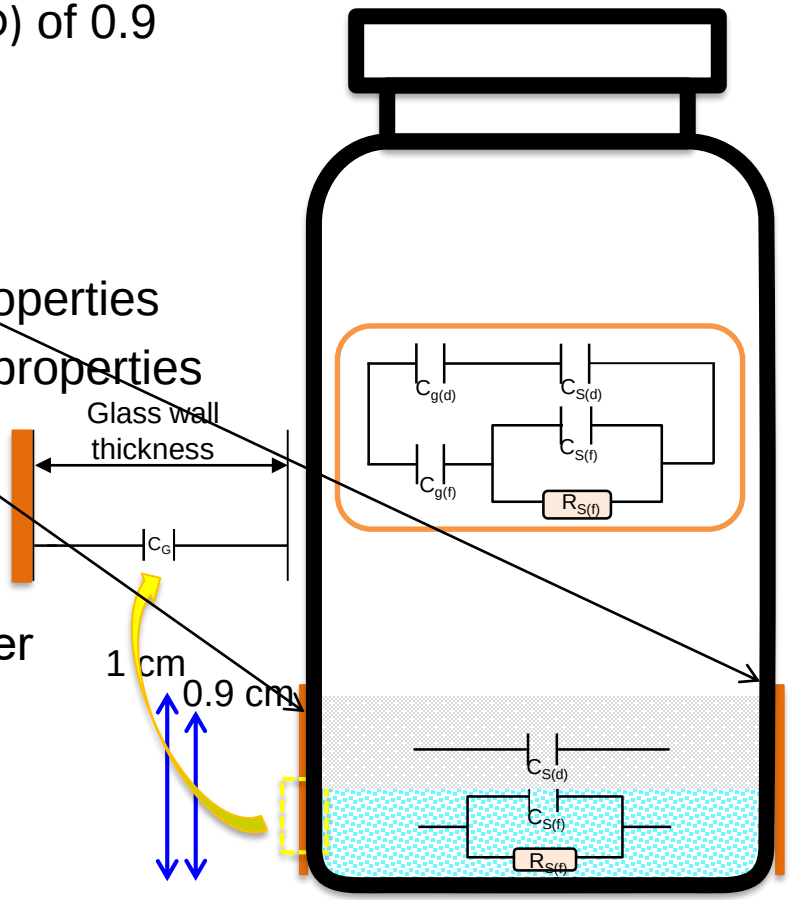


Through Vial Impedance Spectroscopy (TVIS)

- **Electrodes** are attached to the external surface of a vial
- The vial is filled with the sample to fill factor (Φ) of 0.9

$$\text{Fill factor } (\Phi) = \frac{\textit{The height of liquid fill}}{\textit{The height of active electrode}}$$

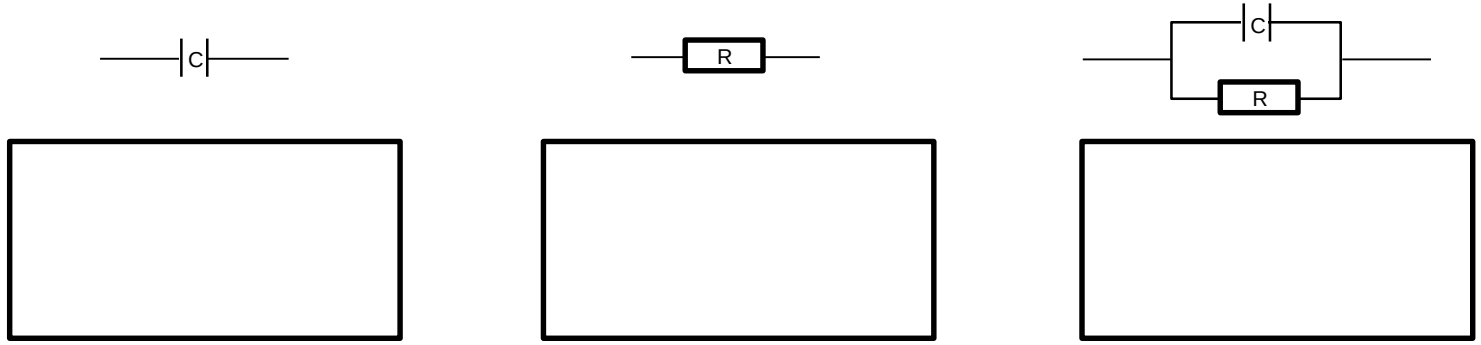
- The sample has both resistive & capacitive properties
- The glass vial has both resistive & capacitive properties
- But glass resistance is so high therefore it behaves primarily as a capacitor.
- In freeze drying, the sample is frozen and dried by sublimation to obtain a 'dry' layer
- The dry layer is predominantly capacitive due to its low moisture content / high resistance
  Exception - Proteins



Through Vial Impedance Spectroscopy (TVIS)

- Impedance is a frequency dependent parameter largely because the impedance of a capacitance is dependent on the frequency of the applied field, whereas an ideal resistor has zero frequency dependence

- In the boxes show small impedance spectrum of log |Z| vs log f for a capacitator and a another spectrum for a resistor, then show a spectrum with R and C in parallel



- By fitting the impedance spectrum one can extract the sample resistance and capacitance

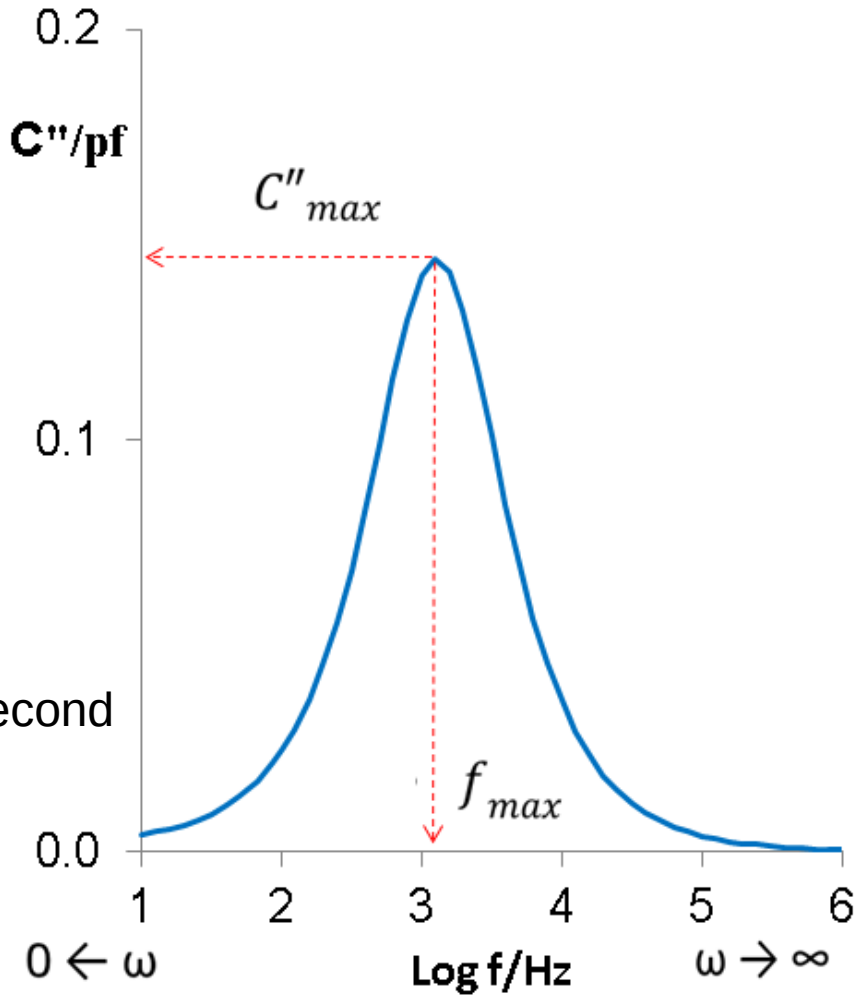
Imaginary Part Capacitance : Characteristic Response

- At ω→0, $C^{"} = 0$
- As the frequency increase, $C^{"}$ increases to maximum ($C^{"}_{max}$) then decreases to 0 as the frequency ω→∞
- At a frequency of

$$\omega_{max} = \frac{1}{R_s(C_S+C_G)}$$ in radians

$$f_{max} = \frac{1}{2\pi Rs(Cs+CG)}$$ in cycles per second

$$C''_{max} = \frac{C_G{}^2}{2(CS+CG)}$$

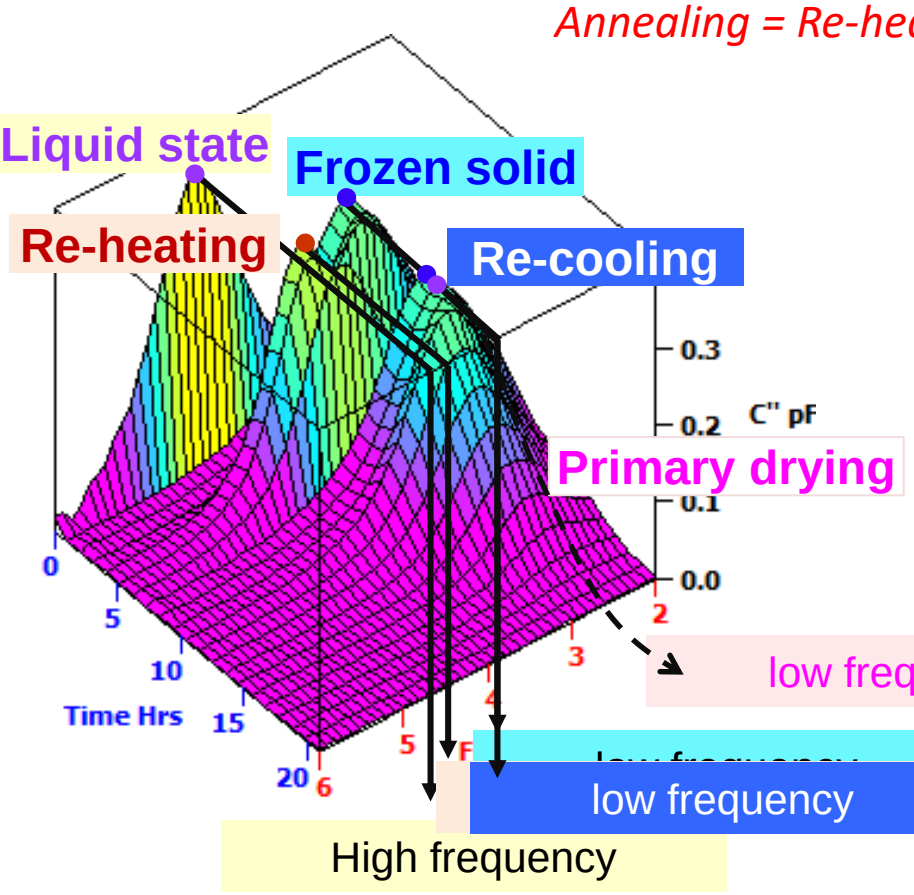


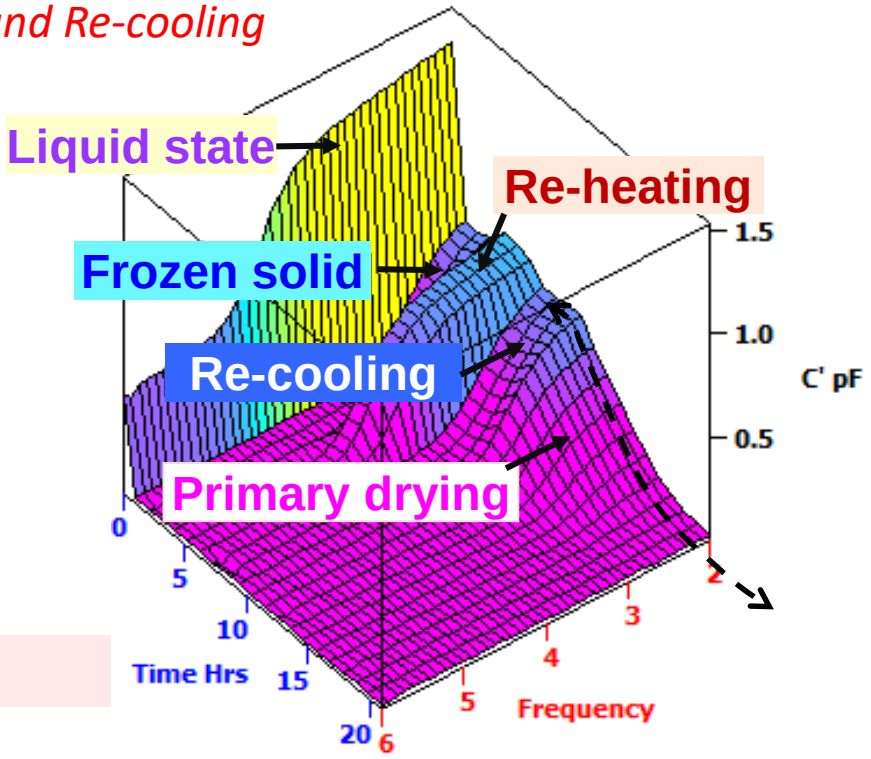
TVIS response surface

Imaginary Part of Capacitance

Real Part of Capacitance

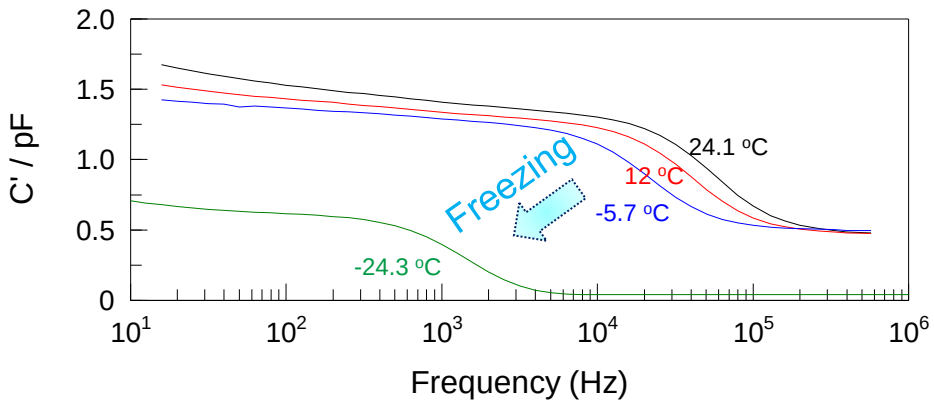
Annealing = Re-heating and Re-cooling

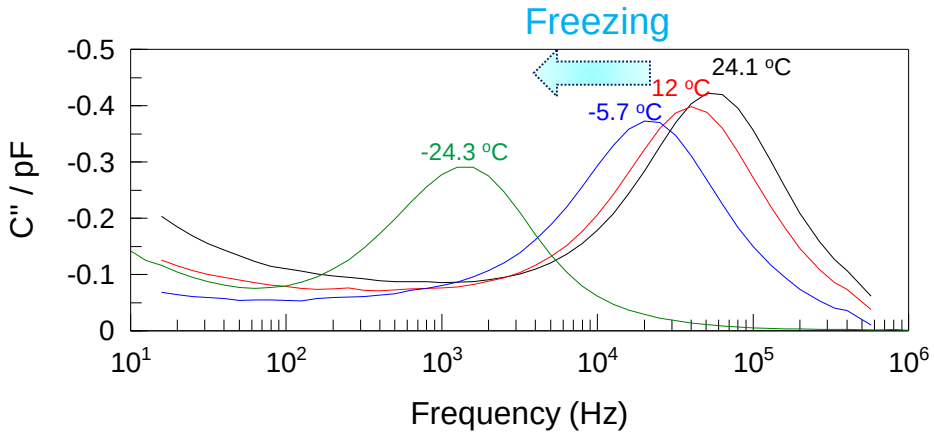




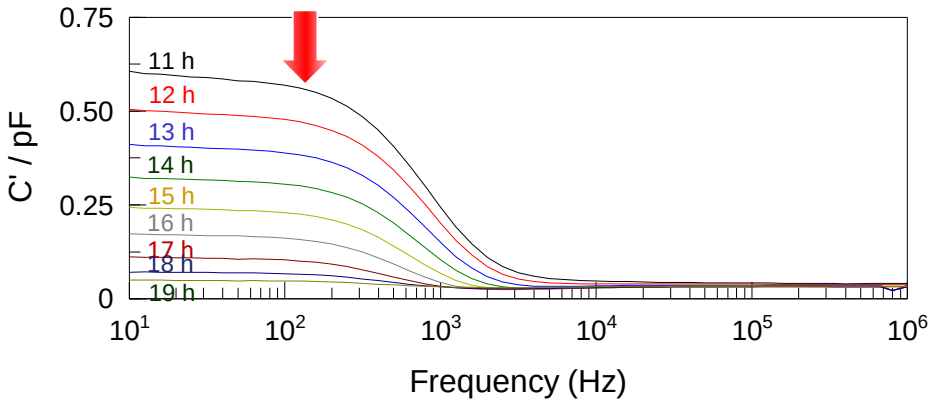
TVIS response surface

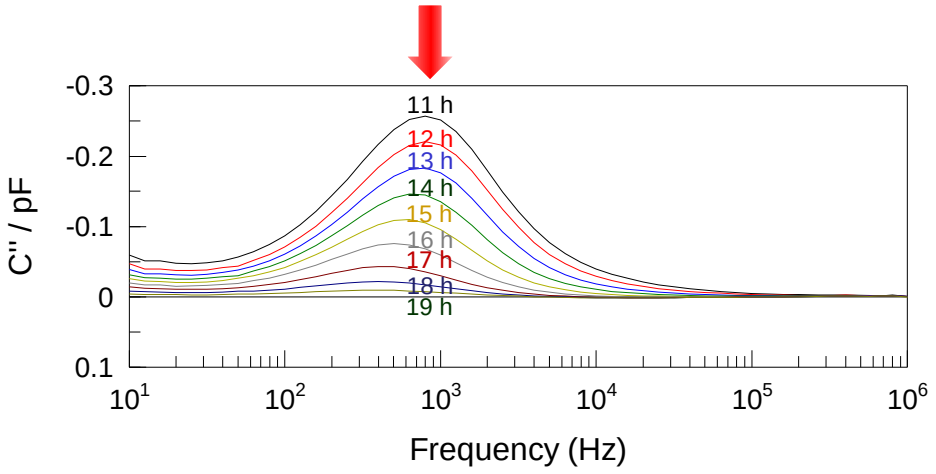
Freezing Process





Primary Drying Process

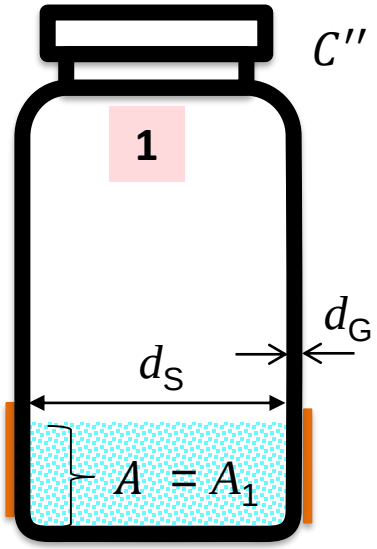




- The magnitudes of C_G and C_S are proportional to the area of interface between the frozen mass and the glass adjacent to the electrode (A).

$$C_G = \frac{\varepsilon_G \varepsilon_o}{d_G} A \qquad C_S = \frac{\varepsilon_S \varepsilon_o}{d_S} A$$

Constant (K_G) Constant (K_S)

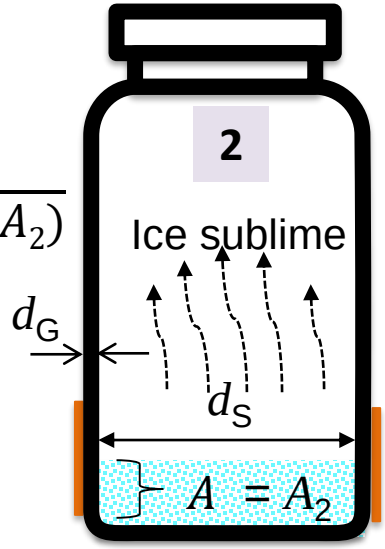


$$C''_{max1} = \frac{C_G^2}{2(Cs + CG)} = \frac{(K_G A_1)^2}{2(K_S A_1 + K_G A_1)} = kA_1$$

$$C''_{max2} = \frac{C_G^2}{2(Cs + CG)} = \frac{(K_G A_2)^2}{2(K_S A_2 + K_G A_2)} = kA_2$$

Primary Drying

$$C''_{max1} > C''_{max2}$$



- In case of a flat sublimation interface, the interfacial area between the frozen layer and the juxtaposed glass wall (A) will decrease in proportion to the remaining ice volume

TVIS Technology: Principle

- The capacitance spectrum is dependent on both *the electrical resistance and electrical capacitance of the vial contents.*
  - Data viewing software (LyoView ™) identifies the peak frequency (F_{PEAK}) and peak amplitude (C''_{PEAK}) in the imaginary part of the capacitance spectrum
- In general terms:
  - F_{PEAK} can be used to monitor phase behaviour (ice formation, glass transitions) and product temperature
  - C''_{PEAK} can be used to monitor the amount of ice remaining during primary drying, from which the drying rate and end point may be determined.

TVIS Application
Heat Transfer Coefficient (K_V) Determination
(Test sample: 2 mL water in 10 mL vial)

Primary Drying Modelling : Heat and Mass Transfer

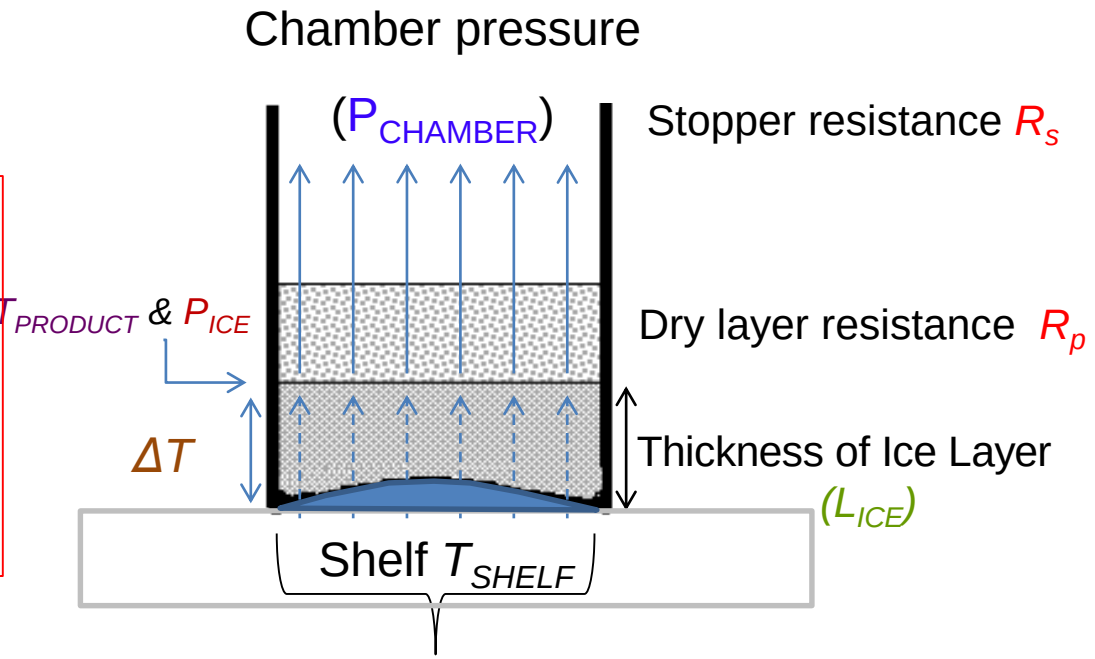
$$\frac{dm}{dt} = \left(\frac{P_{ICE} - P_{CHAMBER}}{\hat{R}_{PS}}\right) \cdot A_P$$

$$\frac{dq}{dt} = L\left(\frac{dm}{dt}\right)$$

K_V determination

$$\frac{dq}{dt} = A_V \boldsymbol{K_V} (T_{SHELF} - T_{PRODUCT})$$

$$\ln(PICE) = \left(\frac{-6144.96}{T_{PRODUCT}}\right) + 24.02$$



dm/dt - sublimation rate (g/hour/vial)

P_{ICE} - Vapour pressure at ice sublimation interface (Torr)

$P_{CHAMBER}$ - Chamber pressure (Torr)

$\hat{R}_{PS}$- Area normalized product and stopper Resistance

dq/dt - heat flow to the product

L - Latent heat of sublimation (J g^{-1})

A_V - cross-sectional area of the vial (cm^2)

T_{SHELF} - Shelf temperature (K)

$T_{PRODUCT}$ - Product temperature at the bottom of vial (K)

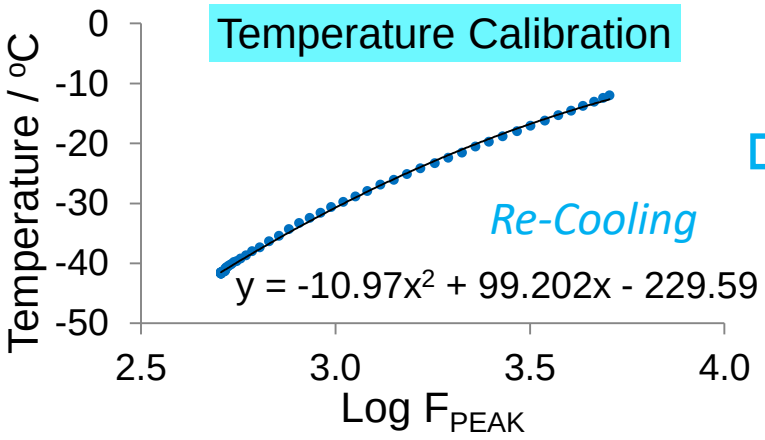
L_{ICE} - Thickness of the ice layer calculated (cm)

ΔT - Temperature different between ice sublimation front and the bottom of the vial (K)

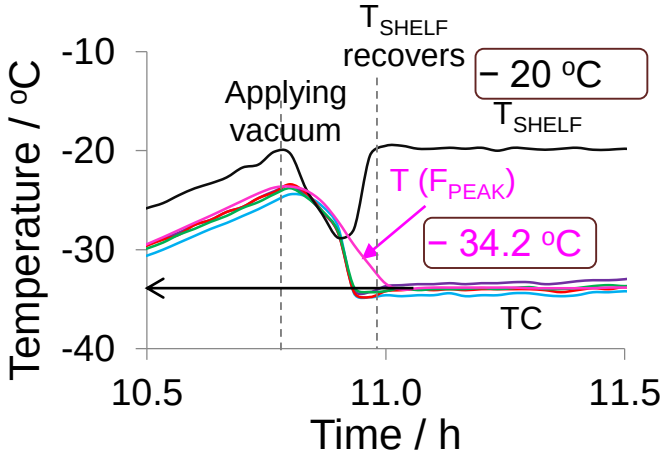
TANG, X.C., NAIL, S.L. and PIKAL, M.J. (2005) Freeze-drying process design by manometric temperature measurement: design of a smart freeze-dryer. Pharmaceutical Research, 22 (4), pp. 685-700.

Heat Transfer Coefficient (K_V) Determination

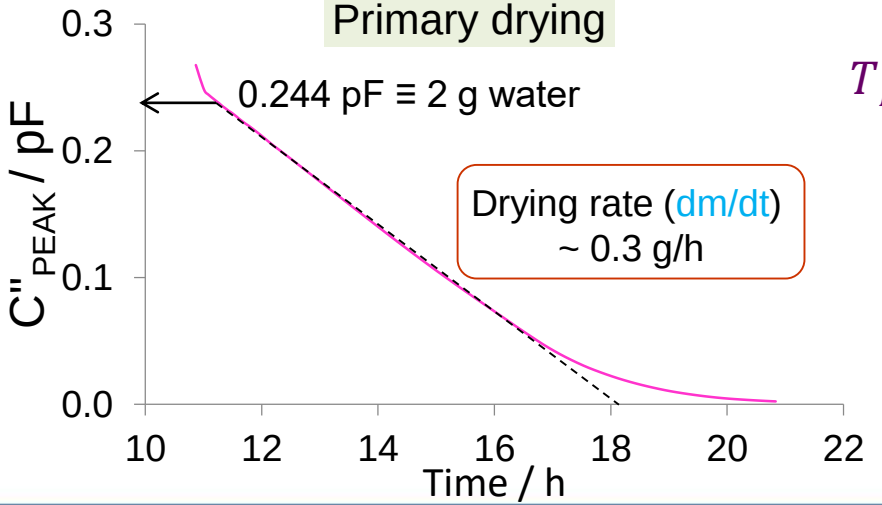
- The product temperature ($T_{PRODUCT}$), which derived by ***TVIS*** as $T(F_{PEAK})$ or *by thermocouple (TC),* is one of parameters needed for K_V determination



Calculate $T_{PRODUCT}$ from Log F_{PEAK} (TVIS)



- Sublimation rate (*dm/dt*) is estimated by ***TVIS***
- Test sample is 2 mL water filled in 10 mL vial



$T_{PRODUCT}$ and *dm/dt* from ***TVIS***

K_V determination

Heat Transfer Coefficient (K_V) Determination

First convert dm/dt to dq/dt using the latent heat of sublimation *(L = 2844 J g^{-1})*

$$L \frac{dm}{dt} = \frac{dq}{dt}$$

d*m*/d*t* = 0.3 g/h

L = 2844 J g^{-1}

d*q*/d*t* = 853 J/h

$$\frac{dq}{dt} = A_V K_V (T_{SHELF} - TPRODUCT)$$

T_{SHELF} = − 20 °C

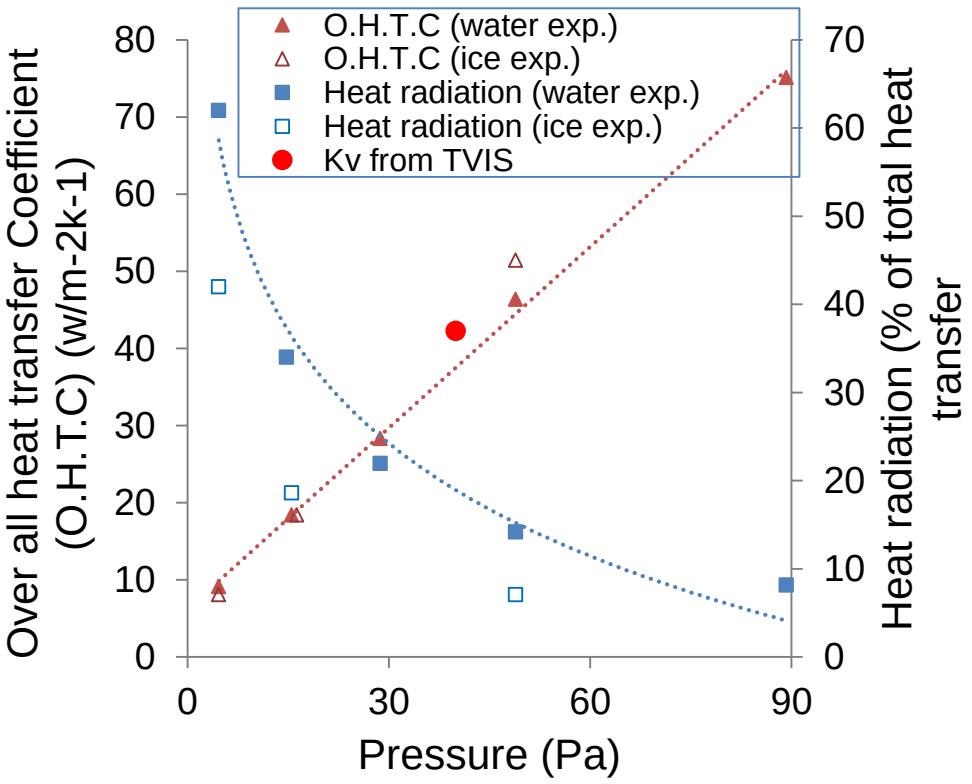
$T_{PRODUCT}$ = − 34.2 °C

A_v = 0.0045 m^2

(*Schott Type1 glass 10 ml tubing vial*)

K_v = 37 W m^{-2} K^{-1} [@ 40 Pa, 400 µBar]

K_v values for 10 mL tubing vials (2 mL fill volume)



Brülls, M., and Ramusson, A. (2002) Heat Transfer in Lyophilization. Int J Pharm 10;246(1-2):1-16.

TVIS Application
Heat Transfer Coefficient (K_V) Determination
(Test sample: 2 mL protein solution fill in 10 mL vial)

Dried Product Resistance (R_P) Determination of Protein Solution

- The different types of resistance to mass transport (water vapour flow)

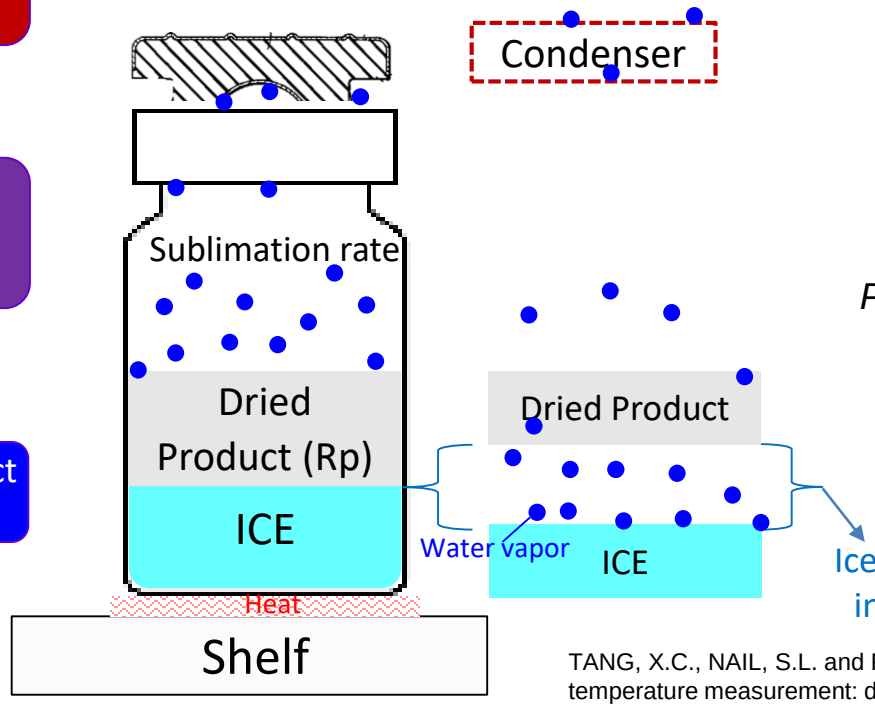
$$\frac{dm}{dt} = \left(\frac{P_{ICE} - PCHAMBER}{R_P + RS + NRC}\right) \Rightarrow \frac{dm}{dt} = \left(\frac{P_{ICE} - P_{CHAMBER}}{\hat{R}p}\right) \cdot A_P$$

Chamber to condenser resistance

Semi-stoppered resistance

Dried product resistance

Product resistance (R_P) is dominated around 80% of the mass transfer therefore the other resistances could be ignored (Pikal, Roy and Shah (1984).



dm/dt = the rate of mass transfer for the water vapour or sublimation rate (g/hour/vial)

P_{ICE} = the equilibrium vapour pressure of ice at the sublimation interface temperature (Torr)

$P_{CHAMBER}$ = the chamber pressure (Torr)

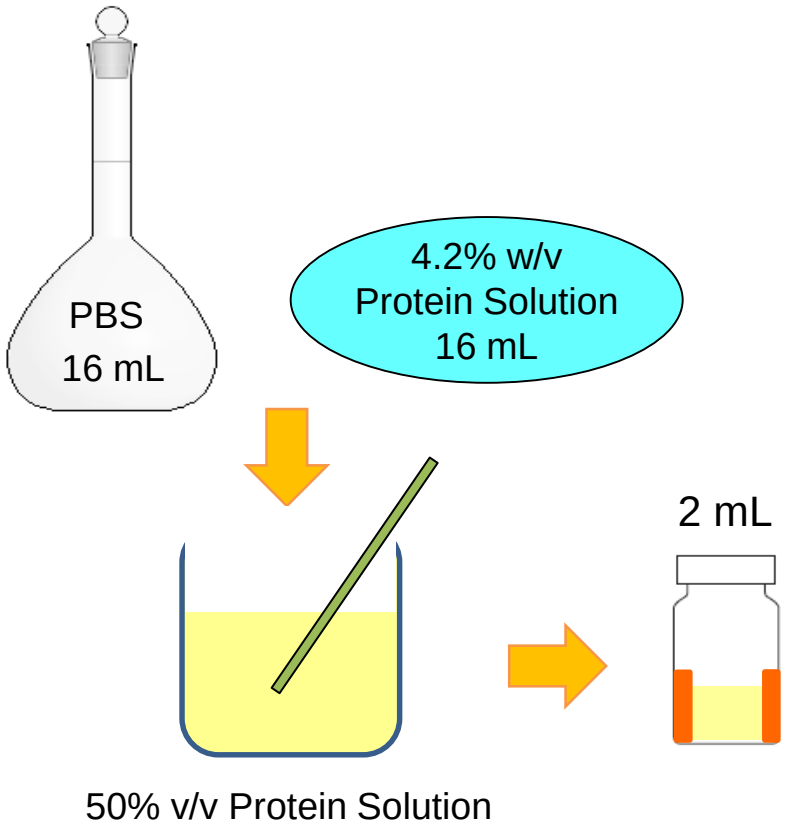
$\hat{R}p$ = the area normalized resistance of the dried product ($cm^2 \cdot Torr \cdot h \cdot g^{-1}$)

Ap = the cross-sectional area of the product (cm^2)

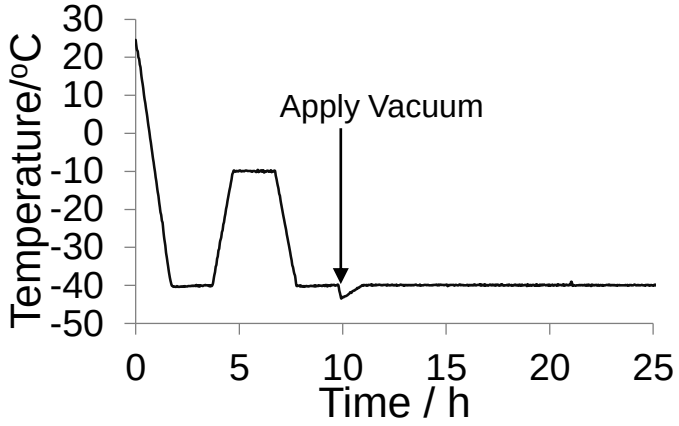
TANG, X.C., NAIL, S.L. and PIKAL, M.J. (2005) Freeze-drying process design by manometric temperature measurement: design of a smart freeze-dryer. Pharmaceutical Research, 22 (4), pp. 685-700.

Dried Product Resistance (R_P) Determination of Protein Solution

Preparation: 50% v/v Protein Solution

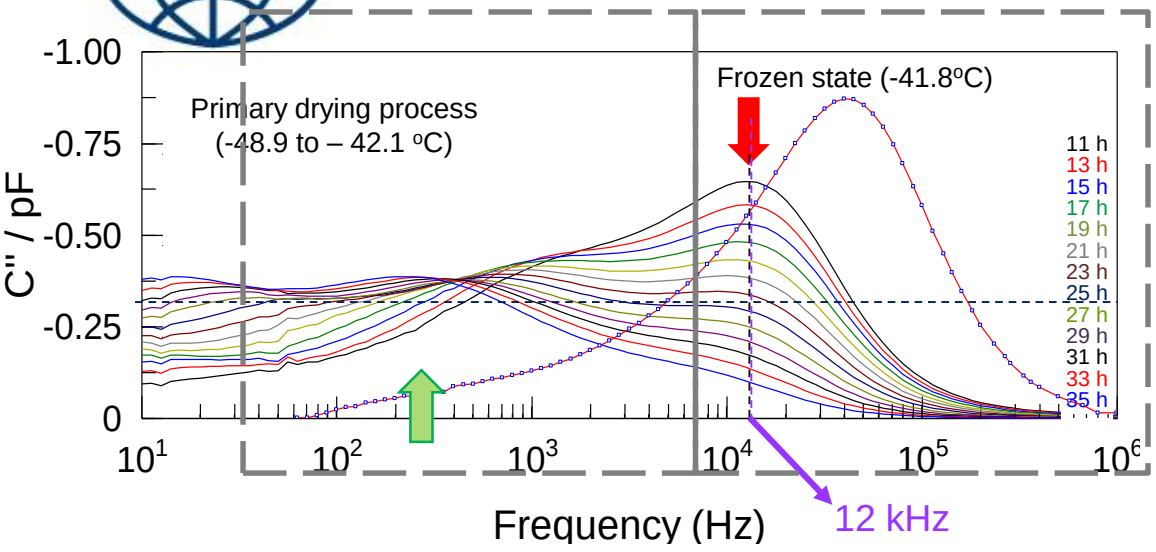


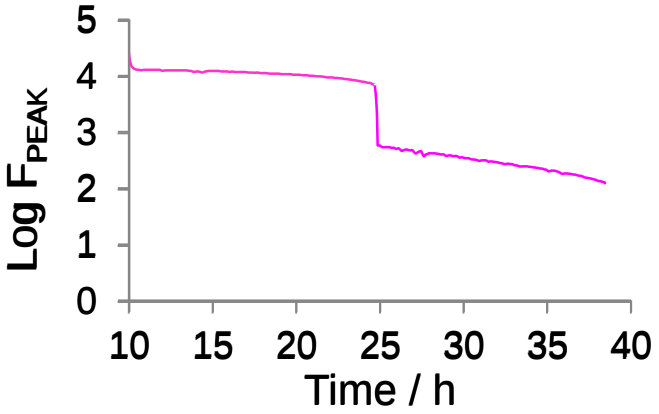
Freeze drying Protocol



- A 50% v/v protein solution 2 mL has protein 0.042 g
- Protein 1 g has unavailable water to colligative effect of ~0.3 g (unfrozen water)
- Therefore unfrozen water of protein is 0.3 x 0.042 = 0.0126 g
- The weight of ice is approximately 2 - 0.0126 = 1.974 g

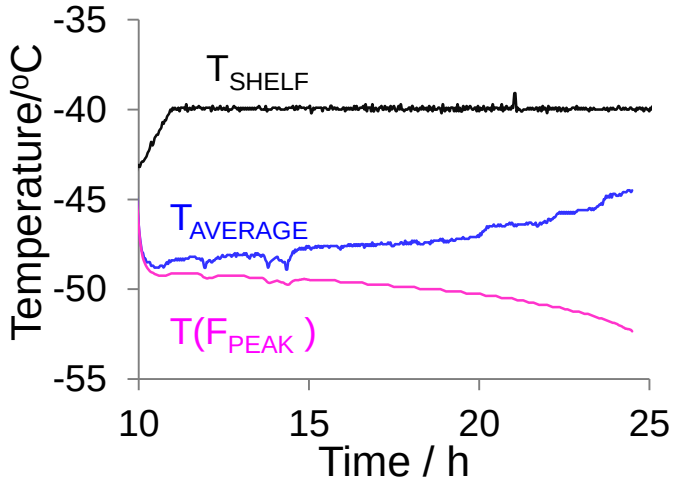
Dried Product Resistance (R_P) Determination of Protein Solution





Calibration data for log F_{PEAK} during annealing is used to predict the product temperature ($T(F_{PEAK})$

- The peak at high frequency (~12 kHz) is due to the ice layer
  - Ice layer peak **decreases** during the early stages of primary drying (< 25 h) because the peak amplitude is proportional to the volume of the ice layer
- The peak at low frequency is due to the dry layer
  - Dry layer peak **increases** during the later stages of primary drying (> 27h) because the peak amplitude is proportional to the volume of the dry layer



Dried Product Resistance (R_P) Determination of Protein Solution

$$\frac{dm}{dt} = \left(\frac{P_{ICE} - PCHAMBER}{\hat{R}p}\right) \cdot A_P$$

Ice vapour pressure calculated from $T_{PRODUCT}$ the product temperature (as derived by ***TVIS*** *or Thermocouple*)

Chamber pressure calculated from the temperature of condenser ($T_{CONDENSER}$) (in case of condenser is in the freeze dry chamber)

$$\hat{R}p = \left(\frac{P_{ICE} - PCHAMBER}{\frac{dm}{dt}}\right) \cdot A_P$$

$$\ln(P_{ICE}) = \left(\frac{-6144.96}{T_{PRODUCT}}\right) + 24.02$$

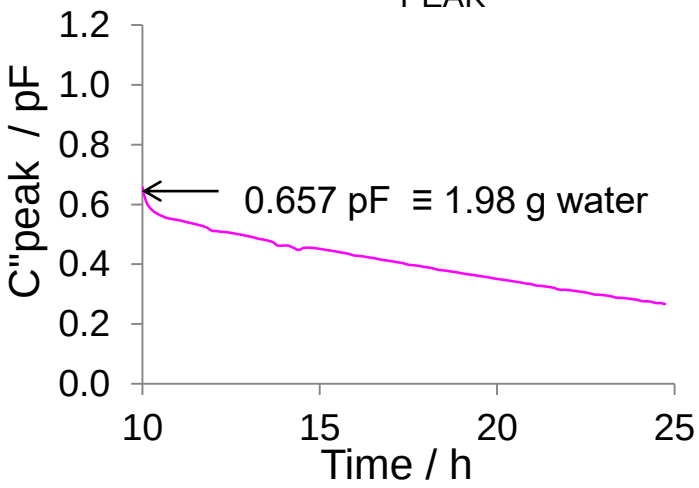
$$\ln(PCHAMBER) = \left(\frac{-6144.96}{T_{CONDENSER}}\right) + 24.02$$

dm/dt can estimate by **TVIS**

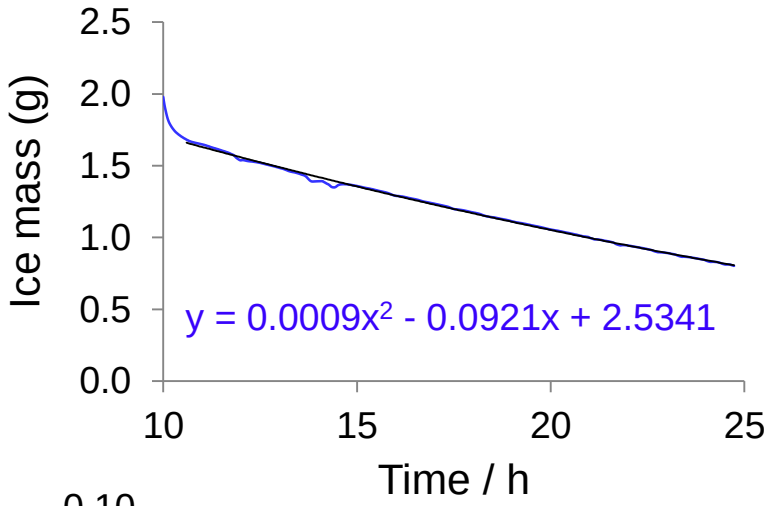
Cross-sectional area of product can calculate by using internal diameter of tested vial ($A = \pi r^2$). *For example, Schott Type1 glass 10 ml tubing vial has internal diameter 2.2 cm therefore,* ***A_P = 3.8 cm²***

Dried Product Resistance (R_P) Determination of Protein Solution

- The drying rate (*dm/dt*) estimated by ***TVIS*** is one of parameters used for determination of dried product resistance (R_P)
- First convert C''_{PEAK} from TVIS to Ice mass



C''_{PEAK} is proportional to the amount of ice



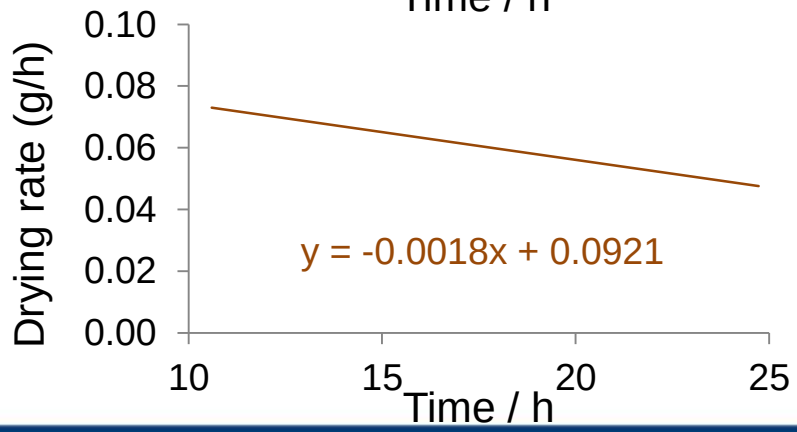
- Then, calculate drying rate (*dm/dt*) using time derivative of ice mass

$y = 0.0009x^2 - 0.0921x + 2.5341$

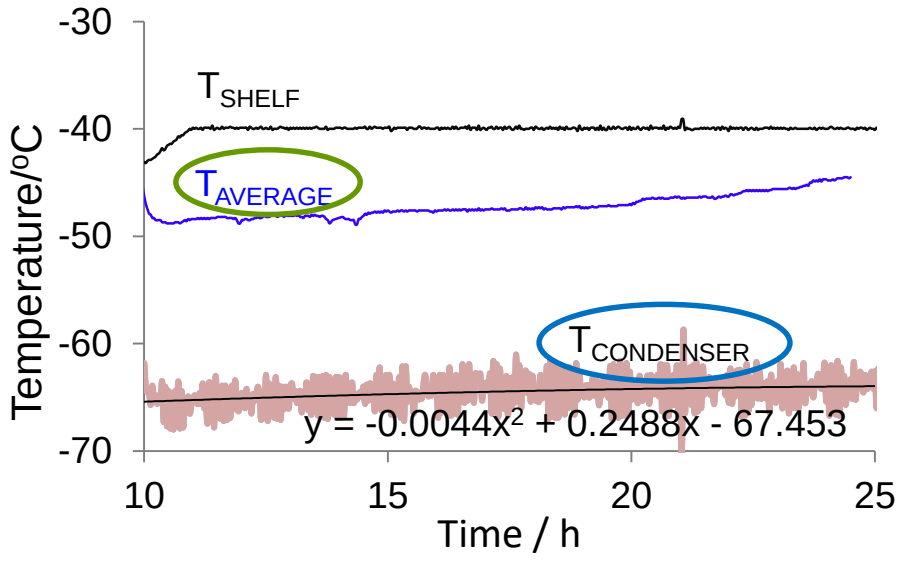
↓

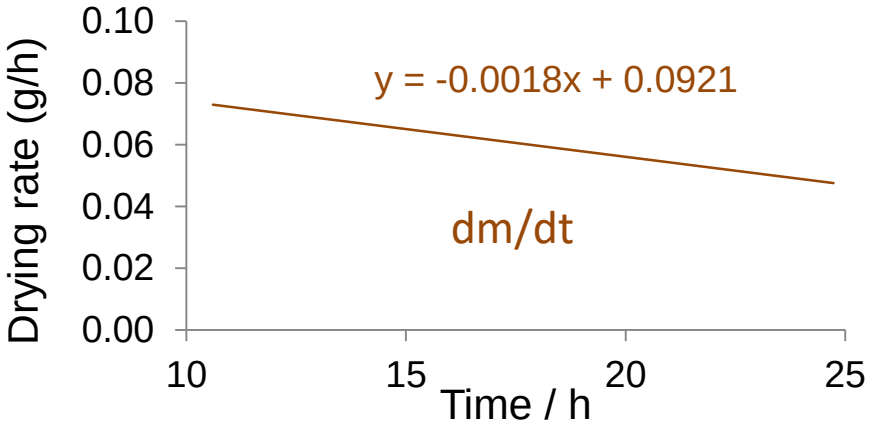
$dm/dt = 0.0018x - 0.0921$

R_p determination



Dried Product Resistance (R_P) Determination of Protein Solution





$$\ln(P_{ICE}) = \left(\frac{-6144.96}{T_{PRODUCT}}\right) + 24.02$$

$$\ln(P_{CONDENSER}) = \left(\frac{-6144.96}{T_{CONDENSER}}\right) + 24.02$$

A_p = 3.8 cm²

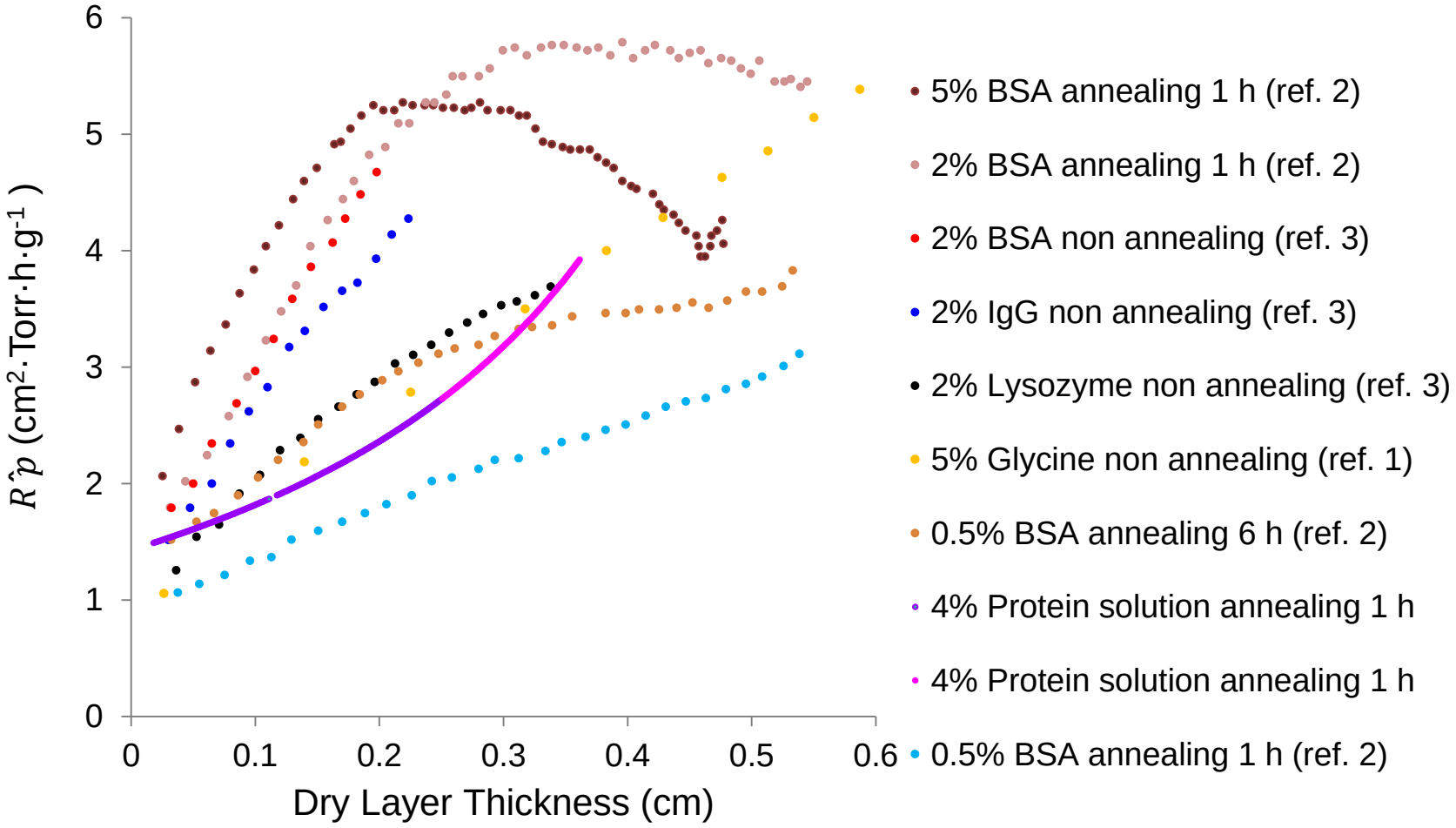
(Schott Type1 glass 10 ml tubing vial)

dm/dt

$$\hat{R}p = \left(\frac{P_{ice} - PC}{\frac{dm}{dt}}\right) \cdot A_P$$

New slide showing the relationship between ice remaining and dry layer thickness

Dried Product Resistance (R_P) Determination of Protein Solution



1. GIESELER, H., KRAMER, T. and PIKAL, M.J. (2007); 2. JOHNSON, R.E. et al. (2010); 3. LEWIS, L.M. et al (2010)

Summary & Future Work

K_v value determination possible.

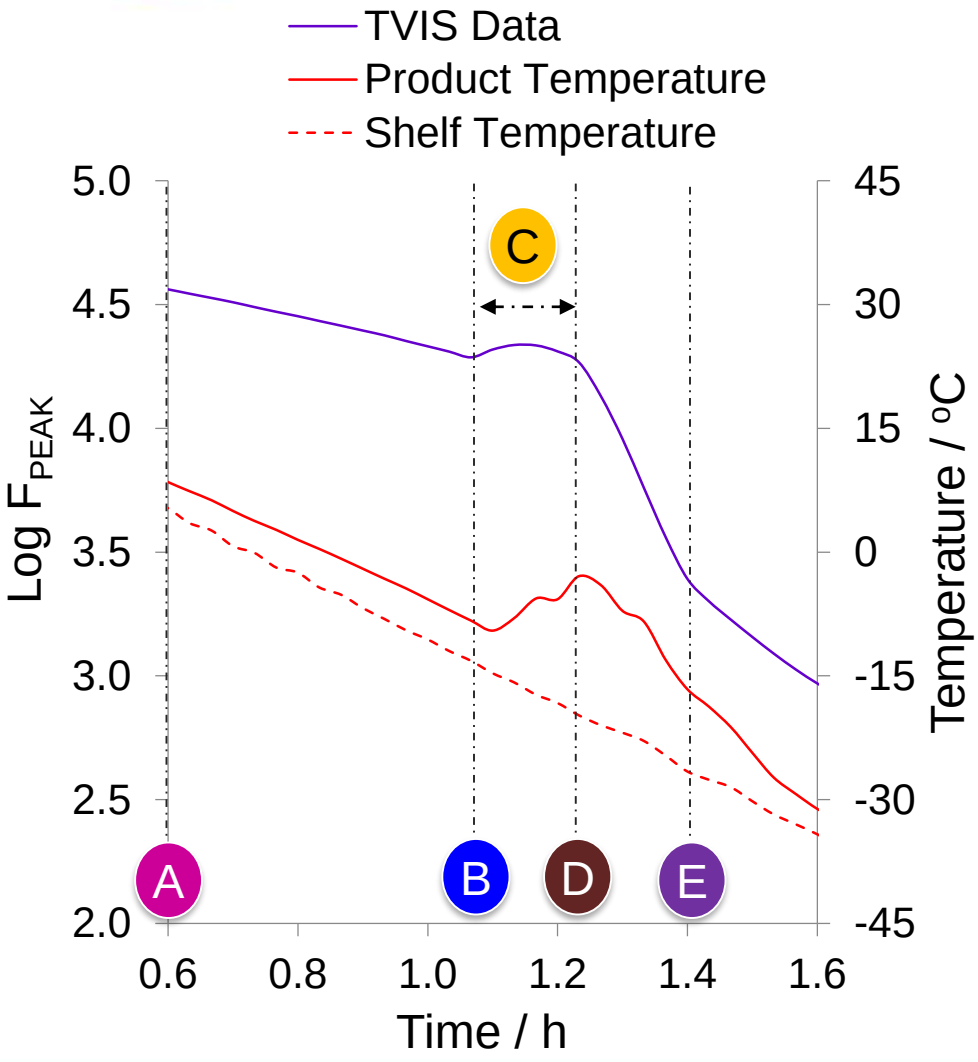
- Increase the drying time over which T(Feak) maybe determined by increasing the fill volume of ice.
- Investigate the dependence on chamber pressure for design space determination

R_p value determination possible:

- Investigate uncertainties in temperature measurement to provide for more reliable estimates of Rp
- Use equivalent circuit modelling to fit spectra and develop a model for a TVIS surrogate for temperature
- Characterise a wide range of materials, formulations and process parameters, inc. nucleation temperature, fill volume, freezing rate, annealing

TVIS Application
Other Applications

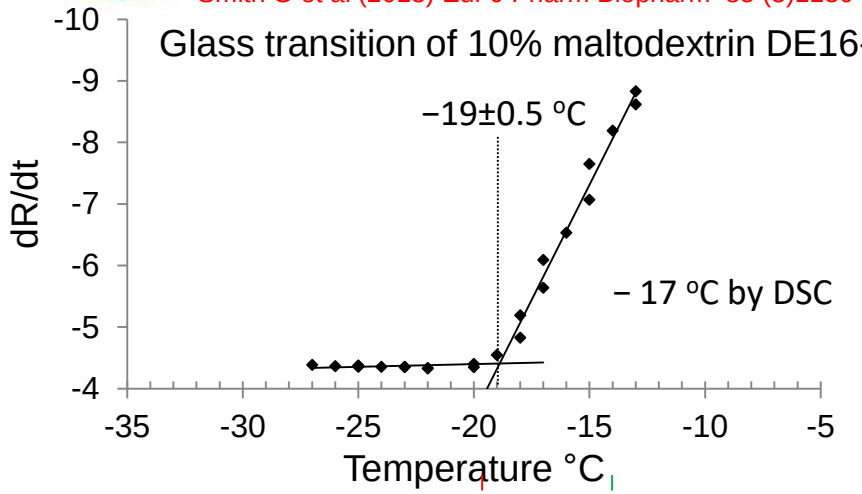
Product characterization: Ice Nucleation



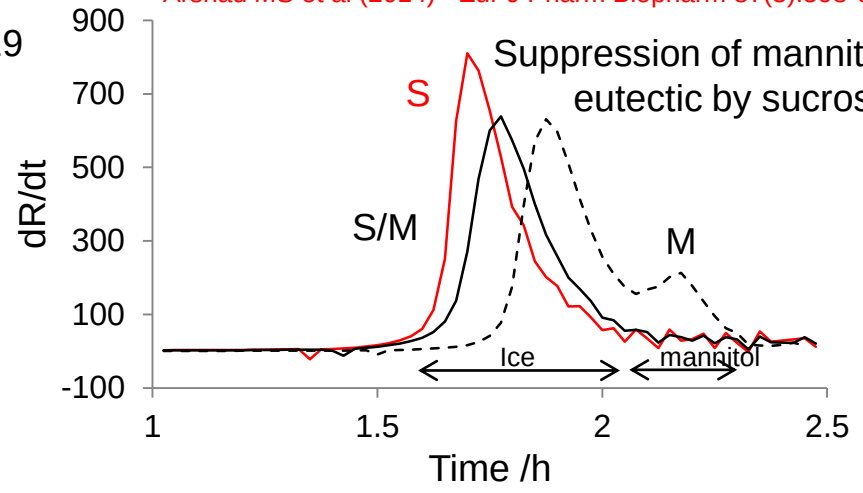
- Log F_{PEAK} profile of freezing step shows the ice nucleation process:
  - Solution is cooled at A
  - Solution super-cools and starts ice nucleation at B This points is referred as *"onset of ice nucleation"*
  - Crystallization or *ice nucleation formation* occurs during C period and continues until the *end point of solidification* at D

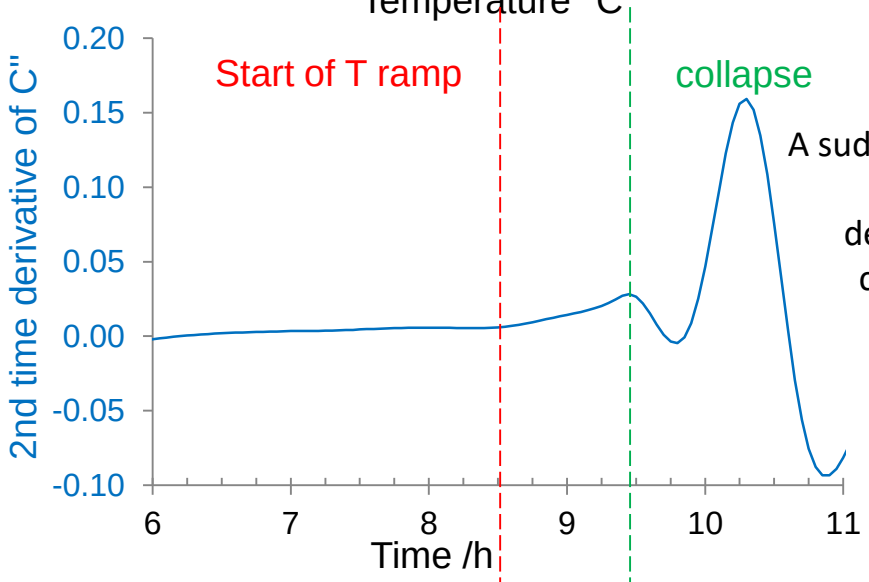
Product characterization: Glass transition, Eutectic Crystallization, Collapse

Smith G et al (2013) Eur J Pharm Biopharm 85 (3)1130-40



Arshad MS et al (2014) Eur J Pharm Biopharm 87(3):598-605





A suddenly change in the capacitance demonstrates the collapse of cake

Smith G et al (2014) Pharmaceutical Technology 38(4)

Summary of Applications of TVIS

- TVIS registers thermal events through changes in the sample resistance associated with
  - Discontinuous changes in viscosity (glass transition, collapse)
  - Change of state (e.g. ice formation and eutectic formation)
- Temperature control might be possible through improved modelling and calibration (Equivalent circuits)
- Primary drying (loss of ice) is monitored through changes in the strength of the dielectric loss peak (or step in the real part capacitance)
  - Enables drying rate determinations for Kv and Rp calculations
- Meso-structural information extracted through the (non-Arrhenius) temperature dependence of the resistance
- Mechanisms of annealing may be elucidated from changes in resistance with time (during the heating-hold phase) and from the absence of any changes in T_G
- Future (with non-contact system)
  - Opportunities to track the physical characteristics over a range of scales, from micro-titre plates to collections of vials

Recent Funding

LyoDEA

£217 160 Collaborative R&D funding

(Nov ’08-Oct ’12) Innovate UK

BioStaRT

£367 567 Collaborative R&D funding

(Aug ’14- Jul ’17) Innovate UK

AtlasBio

£803 846 Collaborative R&D funding

(Oct ’16-Sept 18) Innovate UK

IP: GB2480299

Electrical monitoring of a lyophilization process

Priority Date: 12th May 2010

Assignee: GEA Pharma

DE MONTFORT UNIVERSITY
Evgeny Polygalov. Senior Research Fellow
Yowwares Jeeraruangrattana. Graduate Student
Dr Irina Ermolina. Senior Lecturer

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Genzyme Ireland (Tim McCoy)

Innovate UK for part funding this study

APPENDIX

Through Vial Impedance Spectroscopy (TVIS)

- The impedance of the model can be calculated from the following equation

$$Z^* = \frac{1}{i\omega C*} = \frac{1}{i\omega C_G} + \frac{1}{\frac{1}{R_S} + i\omega C_S}$$

which re-arranges to

$$Z^* = \frac{1}{i\omega C_G} + \frac{R_S}{1 + i\omega R_S C_S} = \frac{1 + i\omega R_S(C_G + C_S)}{i\omega C_G - \omega^2 R C_G C_S}$$

- Impedance can also be expressed in terms of a complex capacitance

$$C^* = C' + C'' = \frac{1}{i\omega Z^*} = \frac{C_G + i\omega R_S C_G C_S}{1 + i\omega R_S(C_G + C_S)}$$

Through Vial Impedance Spectroscopy (TVIS)

- From the complex capacitance formula, the expressions for real and imaginary capacitance can be calculated to explain the origin of interfacial polarization peak. This achieved by multiplying the nominator and denominator by the complex conjugate of the denominator and by grouping the real (C') and imaginary (C'') parts

$$C^* = \frac{1}{i\omega Z^*} = \frac{(C_G + i\omega R_S C_2 C_G)(1 - i\omega R_S(C_S + C_G))}{(1 + i\omega R(C_S + C_G))(1 - i\omega R_S(C_S + C_G))} = \frac{C_G + \omega^2 R_S^2 C_{2G} C_S (C_S + C_G) - i\omega R_S C_G^2}{1 + (\omega R_S((C_S + C_G))^2}$$

To obtain

$$C' = \frac{C_G + \omega^2 R_S^2 C_G C_S (C_S + C_G)}{1 + \left(\omega R_S\left((C_S + C_G\right)\right)^2}$$

and

$$C'' = -\frac{\omega R_S C_G^2}{1 + (\omega R_S((C_S + C_G))^2}$$

Real Part Capacitance

- The value of real part of capacitance at ω→0 is

$$C' = CG_{(fl)} = f(vice)$$

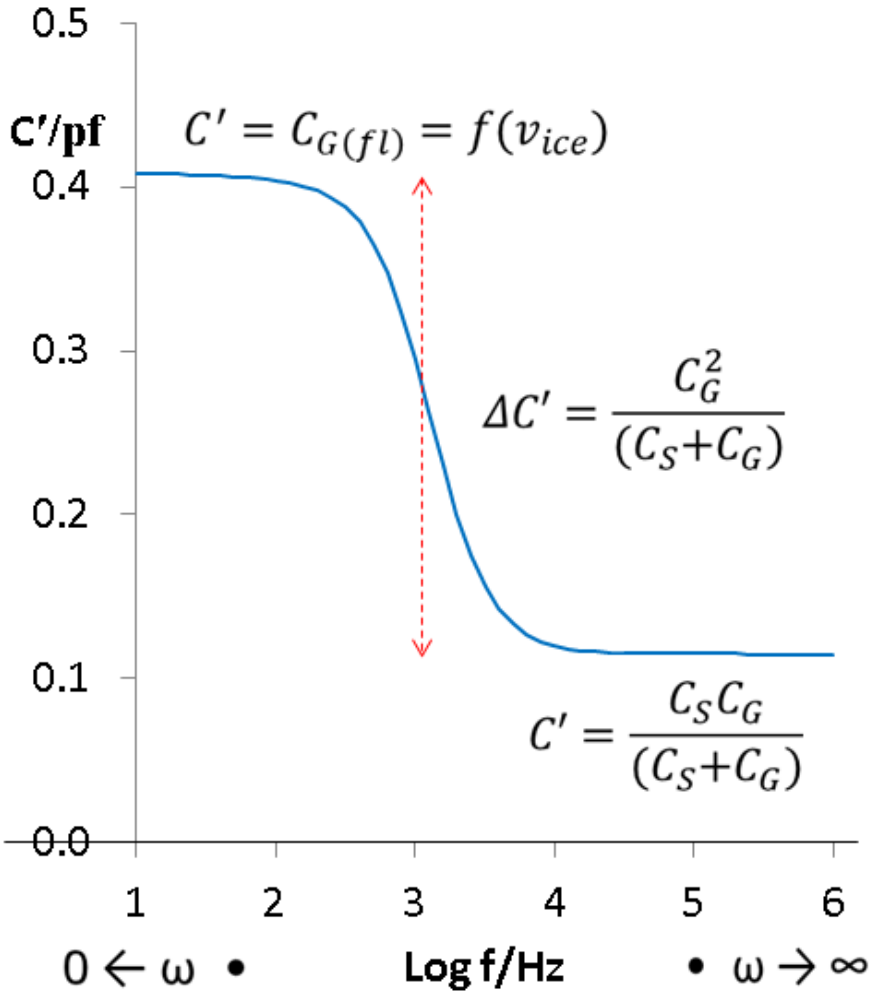
- And the value at ω→∞ is

$$C' = \frac{C_S C_G}{(C_S + C_G)}$$

- It follows that the step change in capacitance is

$$\Delta C' = C_G - \frac{C_S C_G}{(C_S + C_G)}$$

$$\Delta C' = \frac{{C_G}^2}{(C_S + C_G)}$$



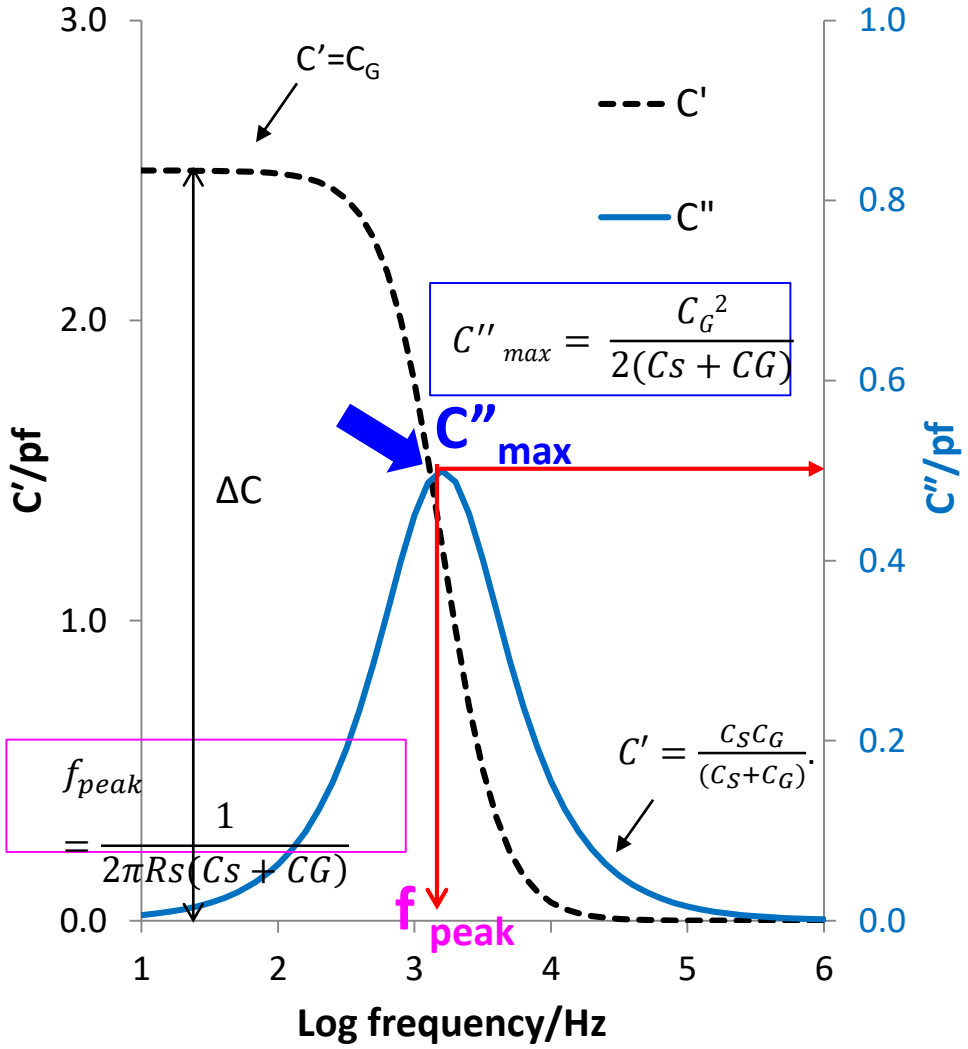
TVIS Technology: Principle

- The peak height is given by

$$C''_{\max} = \frac{C_G{}^2}{2(Cs + CG)}$$

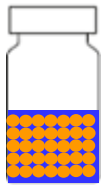
- The peak frequency is given by

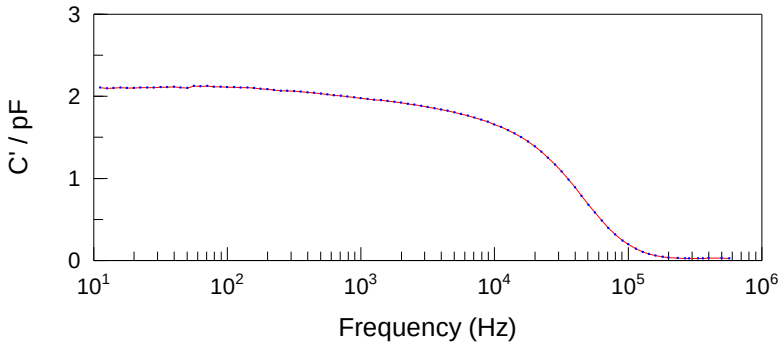
$$f_{peak} = \frac{1}{2\pi Rs(Cs + CG)}$$

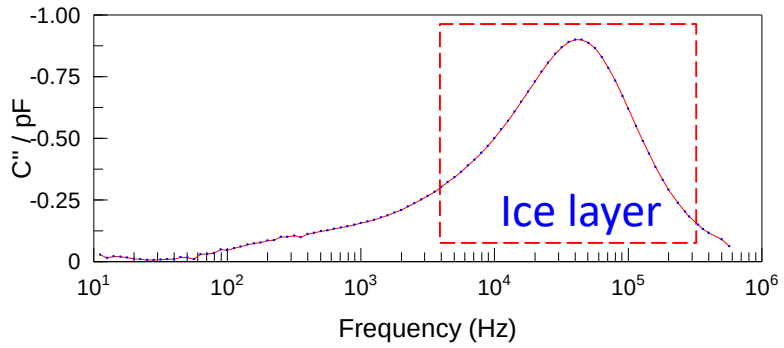


Product characterization: Opportunity for Protein Solution

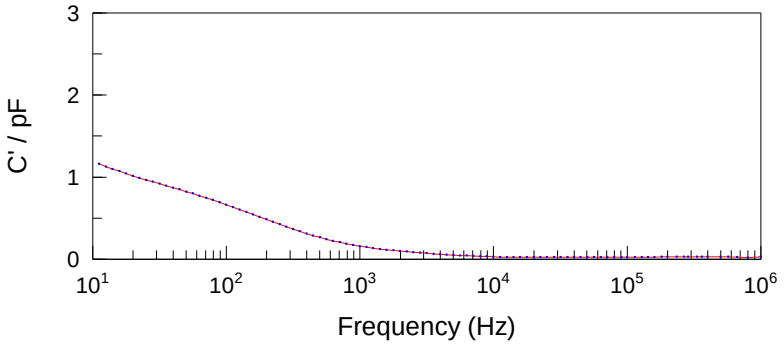
- Low frequency process may hold information on the state/properties of the protein layer, inc. progression and end point of secondary drying

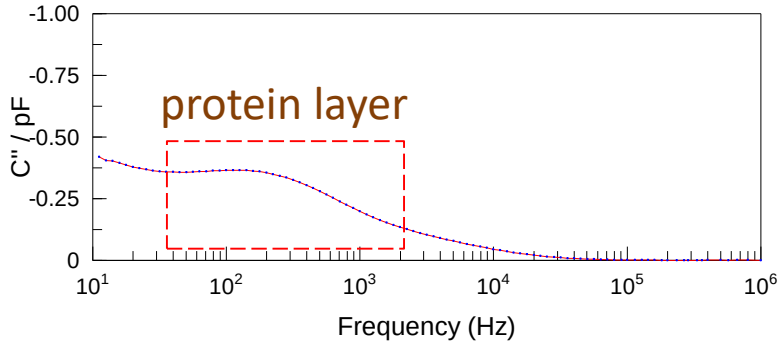




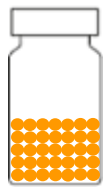


High frequency process
(start of primary drying)





Low frequency process
(end of primary drying)



Dried Product Resistance (R_P) Determination of Protein Solution