Modelling Of Spray and Film Drying: Preliminary Results

S.S. Sazhin and *O. Rybdylova*

The Sir Harry Ricardo Laboratories, School of Computing, Engineering and Mathematics,
University of Brighton, UK

EPSRC Engineering and Physical Sciences Research Council

University of Brighton

Plan

- Background
- Basic equations (droplets)
- Basic equations (film)
- Preliminary results

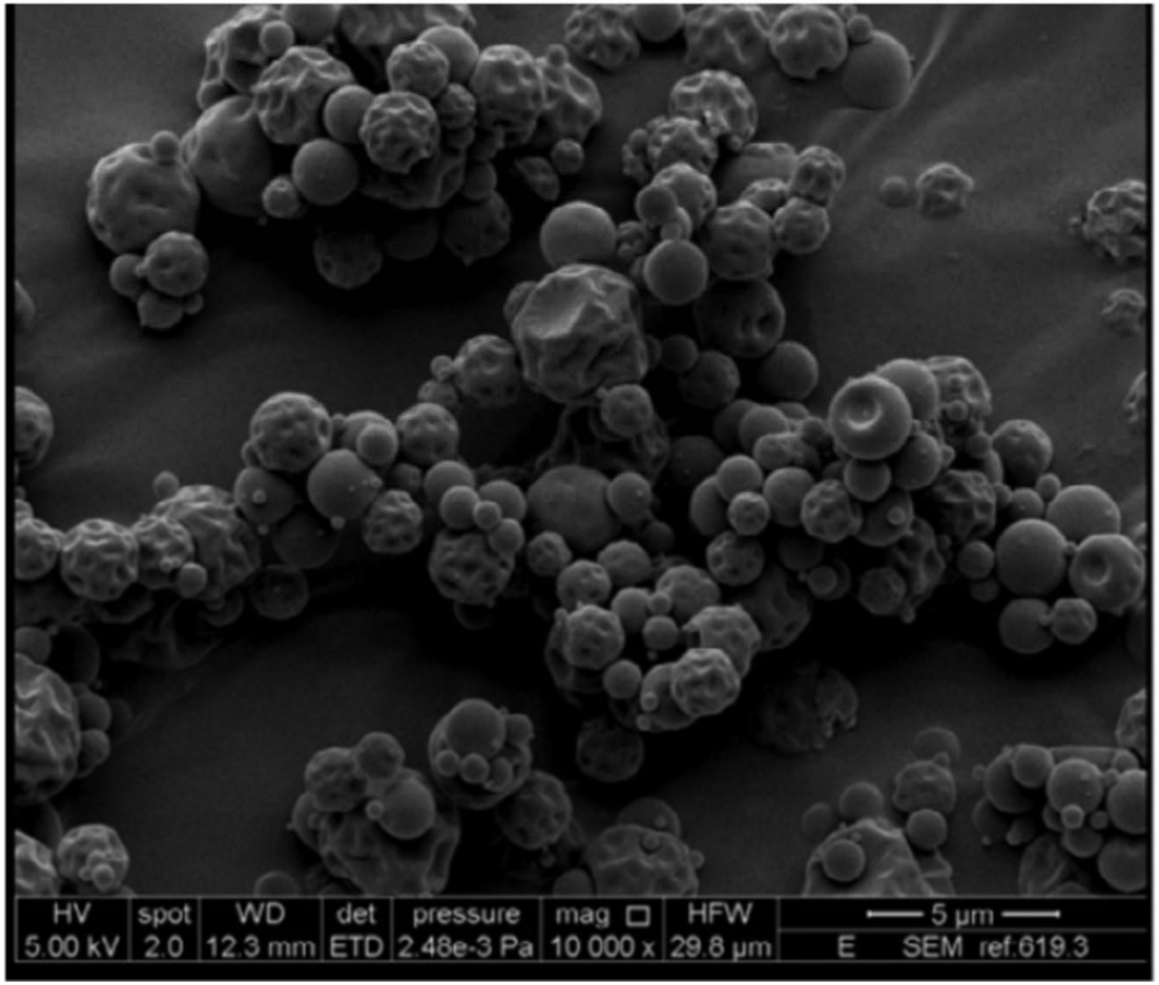
Background

Background

Chitosan (polymer) was weighed on a high accuracy analytical balance and dissolved in de-ionized water. The solution was spray-dried using a lab-scale nanospray dryer equipped with a piezoelectrically driven droplet atomizing technology. The inlet temperature was 120 C, pump flow rate 20 mL/h, gas flow rate 133 L/min, 5.5 µm mesh nozzle and instrument pressure 47 mbar. Spray-dried powders were immediately transferred to a glass vial and kept in a desiccator to prevent crystallization.

The shape and surface morphology of the spray-dried chitosan powder was examined using scanning electron microscopy (SEM) (FEI Quanta 200F SEM; Einhoven, Netherlands). Samples were prepared by placing a small amount of freshly spray-dried powder on an aluminium specimen pin covered with double-sided adhesive carbon tabs (Agor Scientific, UK) followed by sputter coating with gold (Quorum Q150R; Quorum Technologies Ltd., UK) prior to observation under SEM. A typical SEM micrograph for spray-dried chitosan particles is shown in Fig. 1

Background


HV
5.00 kV
spot
2.0
WD
12.3 mm
det
ETD
pressure
2.48e-3 Pa
mag
10 000 x
HFW
29.8 μm
5 μm
E SEM ref.619.3

Basic equations (droplet)

Conduction limit. Effective conductivity

$$c_1\rho_1 \frac{\partial T}{\partial t} = k_1\left(\frac{\partial^2 T}{\partial R^2} + \frac{2}{R}\frac{\partial T}{\partial R}\right) + P\,(R)$$

$$h(T_\mathrm{g} - T_\mathrm{s}) = -\rho_1 L\dot{R}_\mathrm{d} + k_1 \left.\frac{\partial T}{\partial R}\right|_{R=R_\mathrm{d}}$$

$$k_\mathrm{eff} = \chi_T k_l, \qquad T_\mathrm{eff} = T_\mathrm{g} + \frac{\rho_1 L\dot{R}_\mathrm{d}}{h}$$

where the coefficient χ_T varies from about 1 (at droplet Peclet number $\mathrm{Pe}_{d(l)} = \mathrm{Re}_{d(l)}\mathrm{Pr}_l < 10$) to 2.72 (at $\mathrm{Pe}_{d(l)} > 500$) and can be approximated as

$$\chi_T = 1.86 + 0.86 \tanh\left[2.225 \log_{10}\left(\mathrm{Pe}_{d(l)}/30\right)\right].$$

Analytical solution for *h*=const

$$T(R,t)=\frac{R_d}{R}\sum_{n=1}^{\infty}\Big[q_n \exp[-\kappa_R\lambda_n^2 t]-\frac{\sin\lambda_n}{||v_n||^2\lambda_n^2}\mu_0(0)\exp[-\kappa_R\lambda_n^2 t]$$

$$-\frac{\sin\lambda_n}{||v_n||^2\lambda_n^2}\int_0^t \frac{d\mu_0}{d\tau}\exp[-\kappa_R\lambda_n^2(t-\tau)]\,\mathrm{d}\tau\Big]\sin\left[\lambda_n\left(\frac{R}{R_d}\right)\right]+T_g(t)$$

where λ_n are solutions to the equation: $\lambda\cos\lambda+h_0\sin\lambda=0$,

$$||v_n||^2=\frac{1}{2}\left(1-\frac{\sin 2\lambda_n}{2\lambda_n}\right)=\frac{1}{2}\left(1+\frac{h_0}{h_0^2+\lambda_n^2}\right),\qquad \kappa_R=\frac{k_l}{c_l\rho_l R_d^2}$$

$$q_n=\frac{1}{R_d||v_n||^2}\int_0^{R_d}\hat{T}_0(R)\sin\left[\lambda_n\left(\frac{R}{R_d}\right)\right]dR,$$

$$h_0=\frac{hR_d}{k_l}-1 \qquad \hat{T}_0(R)=\frac{RT_{d0}(R)}{R_d} \qquad \mu_0(t)=\frac{hT_g(t)R_d}{k_l}$$

The effect of thermal radiation is not taken into account in this solution.

Discrete components model

$$\frac{\partial Y_{li}}{\partial t} = D_{\text{eff}}\left(\frac{\partial^2 Y_{li}}{\partial R^2} + \frac{2}{R}\frac{\partial Y_{li}}{\partial R}\right)$$

Boundary and initial conditions:

$$\alpha(\epsilon_i - Y_{lis}) = D_{\text{eff}}\frac{\partial Y_{li}}{\partial R}|_{R=R_R-0}$$

$$\frac{\partial Y_{li}}{\partial R}|_{R=0} = 0; \;\; Y_{li}\,(t=0) = Y_{li0}\,(R); \quad R \le R_d$$

Effective diffusivity D_{eff}=$\chi_Y D_l$ where χ_Y=1.86+ 0.86 tanh [2.225 $\log_{10}(\text{Pe}_{dY}/30)$]

χ_Y increases from 1 to 2.72 when Pe_{dY}=Re_dSc increases from <10 to > 500

Sc=ν_l/D_l is the liquid Schmidt number; $\epsilon_i = \frac{Y_{vis}}{\sum_i Y_{vis}}$ $\alpha = \frac{|\dot{m}_d|}{4\pi\rho_l R_d^2}$

Discrete components model

Equation for the partial fuel vapour pressures at the surface of the droplet

$$p_{vis} = \gamma_i X_{lis} p^*_{vis}$$

where X_{lis} is the molar fraction of the *i*th species in the liquid near the droplet surface, p^*_{vis} is the partial vapour pressure of the *i*th species in the case X_{lis}= 1, γ_i is the activity coefficient. In some applications, the latter coefficient can be assumed equal to 1. In this case, this equation leads to the Raoult law

Analytical solution to the species diffusion equation

$$Y_{li}(R,t)=\epsilon_i+\frac{1}{R}\left\{\exp\left[-D_{\mathrm{eff}}\left(\frac{\lambda_0^2}{R_d^2}\right)t\right]\left[q_{Yi0}-\epsilon_i(0)\,Q_{Y0}\right]\sinh\left[\lambda_0\left(\frac{R}{R_d}\right)\right]\right.$$

$$\left.+\sum_{n=1}^{\infty}\left\{\exp\left[-D_{\mathrm{eff}}\left(\frac{\lambda_n^2}{R_d^2}\right)t\right]\left[q_{Yin}-\epsilon_i(0)\,Q_{Yn}\right]\sin\left[\lambda_n\left(\frac{R}{R_d}\right)\right]\right\}\right\}$$

where λ_n are solutions to the equations: $\lambda\cosh\lambda+h_{Y0}\sinh\lambda=0\ (n=0),\quad \lambda\cos\lambda+h_{Y0}\sin\lambda=0\ (n\geq 1),$

$$||v_{Yn}||^2=-\frac{R_d}{2}\left(1+\frac{h_{Y0}}{h_{Y0}^2-\lambda_0^2}\right),\qquad ||v_{Yn}||^2=\frac{R_d}{2}\left(1+\frac{h_0}{h_0^2+\lambda_n^2}\right)\quad(n\geq 1),$$

$$q_{Yn}=\frac{1}{||v_{Yn}||^2}\int_0^{R_d}v_{yn}^2\,(R)\,dR,$$

$$h_{Y0}=-\left(1+\frac{\alpha R_d}{D_{\mathrm{eff}}}\right)$$

$$Q_{Yn}=\begin{cases}-\frac{1}{||v_{Y0}||^2}\left(\frac{R_d}{\lambda_0}\right)^2(1+h_{Y0})\sinh\lambda_0 & \text{when}\quad n=0\\ \frac{1}{||v_{Yn}||^2}\left(\frac{R_d}{\lambda_n}\right)^2(1+h_{Y0})\sin\lambda_n & \text{when}\quad n\geq 1\end{cases}$$

$$\alpha=\frac{|\dot{m}_d|}{4\pi\rho_l R_d^2}$$

Basic equations (film)

Basic equations (temperature)

$$\frac{\partial T}{\partial t} = \kappa_l \frac{\partial^2 T}{\partial x^2}$$

$$h(T_{\text{eff}} - T_s) = k_l \left. \frac{\partial T}{\partial x} \right|_{x=\delta_0 - 0}$$

$$T_{\text{eff}} = T_g + \frac{\rho_l L \dot{\delta}_{0e}}{h},$$

Basic equations (temperature)

$$T(X,t) = T_w + \frac{Xh_0}{1+h_0}(T_{\text{eff}} - T_w) + \sum_{n=1}^{\infty} \exp\left[-\kappa_{\delta 0}\lambda_n^2 t\right]\left[q_n + f_n h_0 (T_{\text{eff}} - T_w)\right]\sin(\lambda_n X), \tag{4}$$

where $X = x/\delta_0$, $h_0 = h\delta_0/k_l$, $\kappa_{\delta 0} = k_l/\left(c_l \rho_l \delta_0^2\right)$,

$$q_n = \frac{1}{\| v_n \|^2}\int_0^1 (T_0(X) - T_w)\sin(\lambda_n X)\mathrm{d}X, \quad f_n = \frac{1}{\| v_n \|^2}\int_0^1 f(X)\sin(\lambda_n X)\mathrm{d}X = -\frac{\sin\lambda_n}{\| v_n \|^2\ \lambda_n^2},$$

$f(X) = -X/(1+h_0)$, $\| v_n \|^2 = \frac{1}{2}\left(1 - \frac{\sin 2\lambda_n}{2\lambda_n}\right) = \frac{1}{2}\left(1 + \frac{h_0}{h_0^2 + \lambda_n^2}\right)$, λ_n are non-trivial solutions to the equation

$$\lambda\cos\lambda + h_0 \sin\lambda = 0. \tag{5}$$

Basic equations (species mass fractions)

$$\frac{\partial Y_{l,i}}{\partial t} = D_l \frac{\partial^2 Y_{l,i}}{\partial x^2}$$

$$D_l \frac{\partial Y_{l,i}}{\partial x}\bigg|_{x=\delta_0-0} = |\dot{\delta}_{0e}| \left(Y_{l,i}|_{x=\delta_0} - \epsilon_i \right),$$

$$\frac{\partial Y_{l,i}}{\partial x}\bigg|_{x=0} = 0,$$

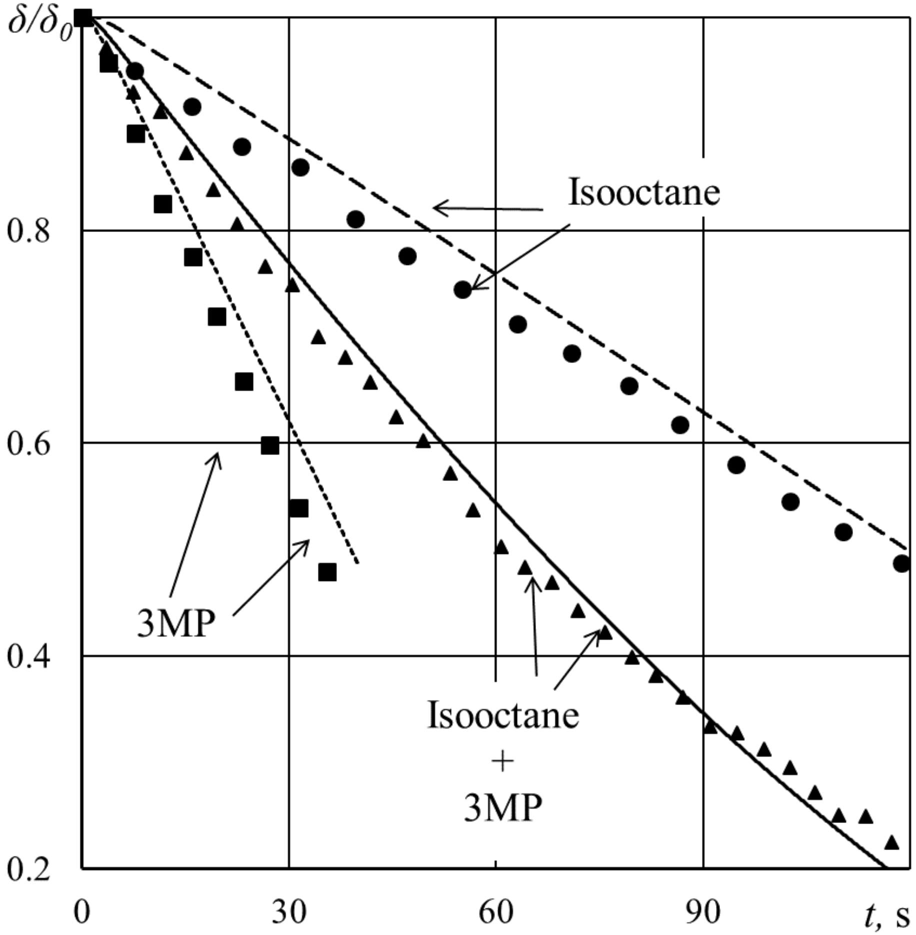
Basic equations (species mass fractions)

$$Y_{vs,i}(t,x) = q_0 \exp\left[D_l \left(\frac{\lambda_0}{\delta_0}\right)^2 t\right] \cosh\left(\lambda_0 \frac{x}{\delta_0}\right) + \sum_{n=1}^{\infty} q_n \exp\left[-D_l \left(\frac{\lambda_n}{\delta_0}\right)^2 t\right] \cos\left(\lambda_n \frac{x}{\delta_0}\right) + \epsilon_i$$

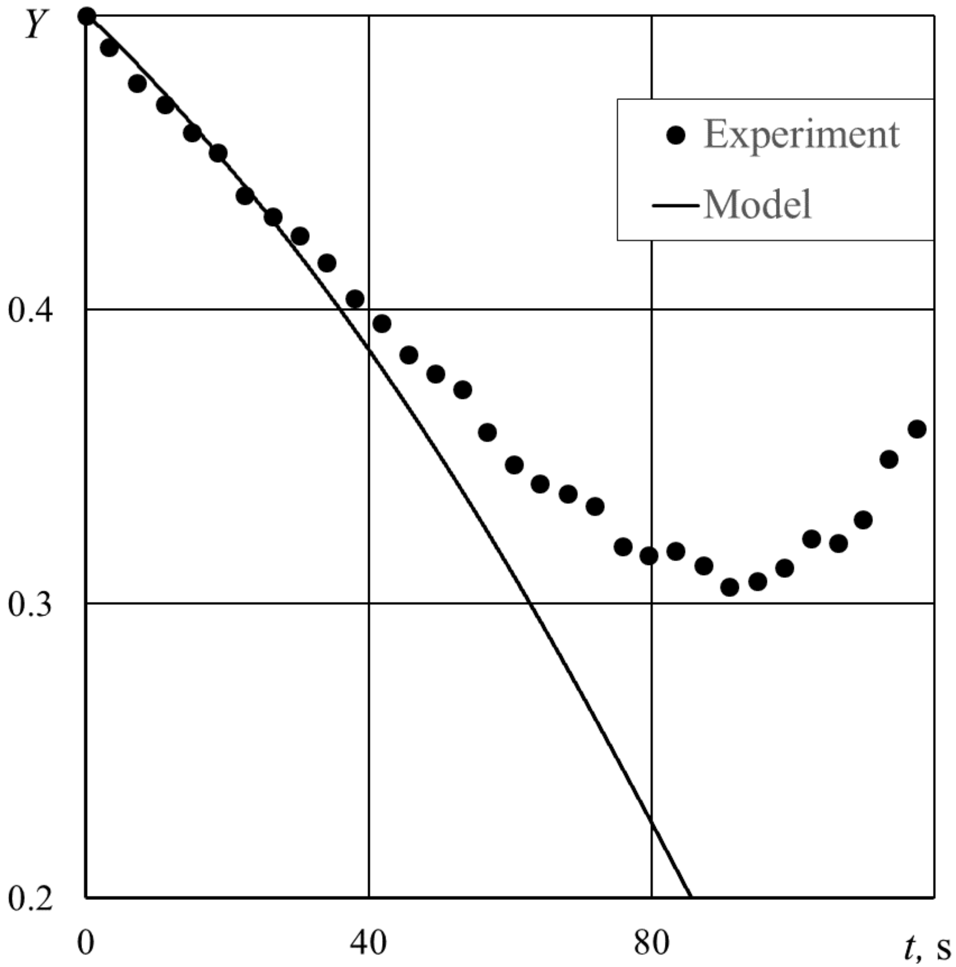
Raoult law

$$p_{vs,i} = X_{ls,i} p^*_{v,i}$$

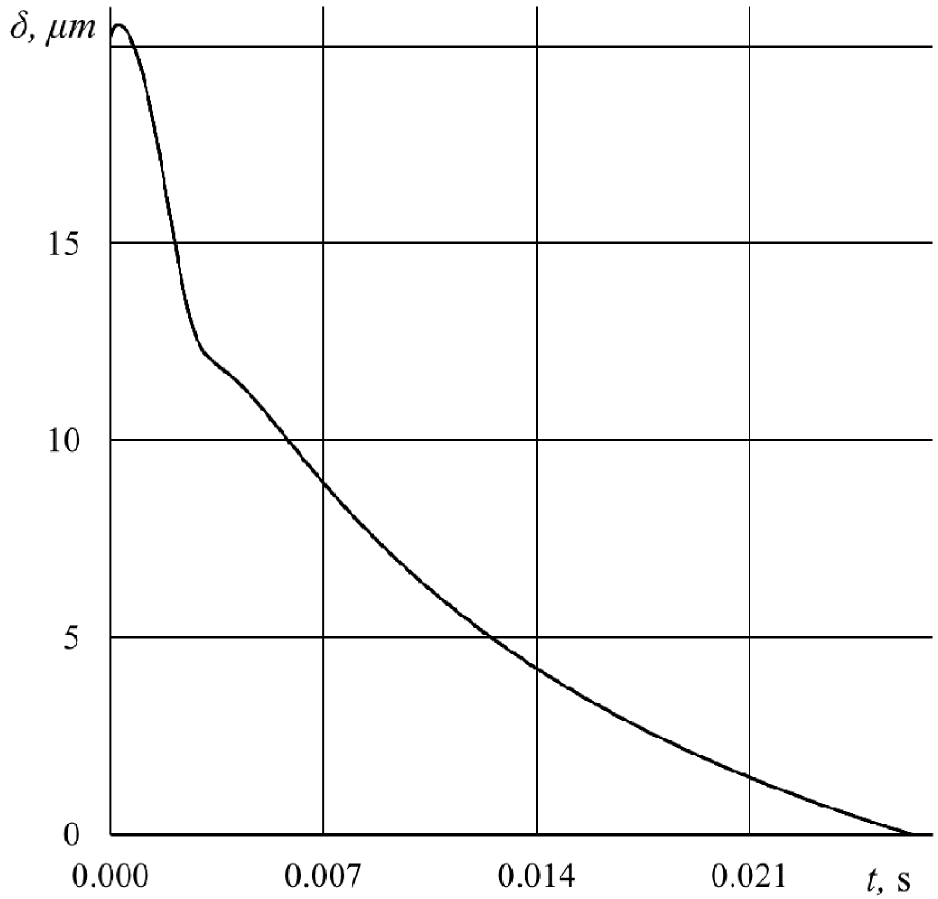
Preliminary results (film)



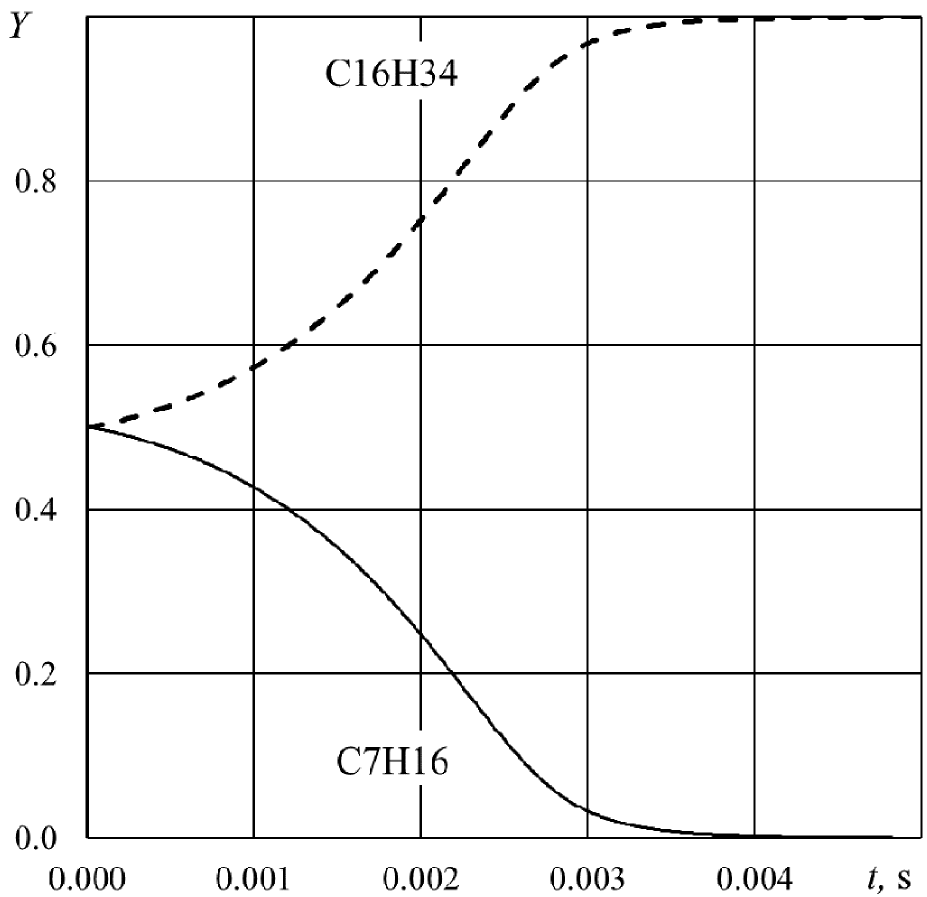
Preliminary results (film)



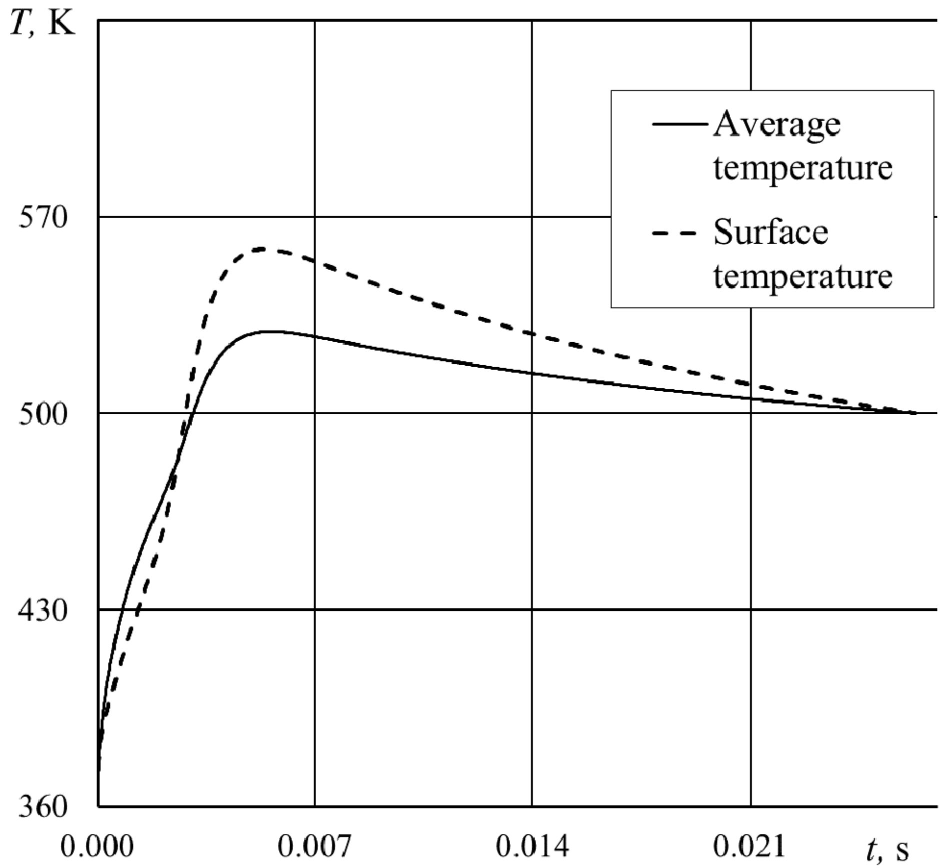
Preliminary results (film)



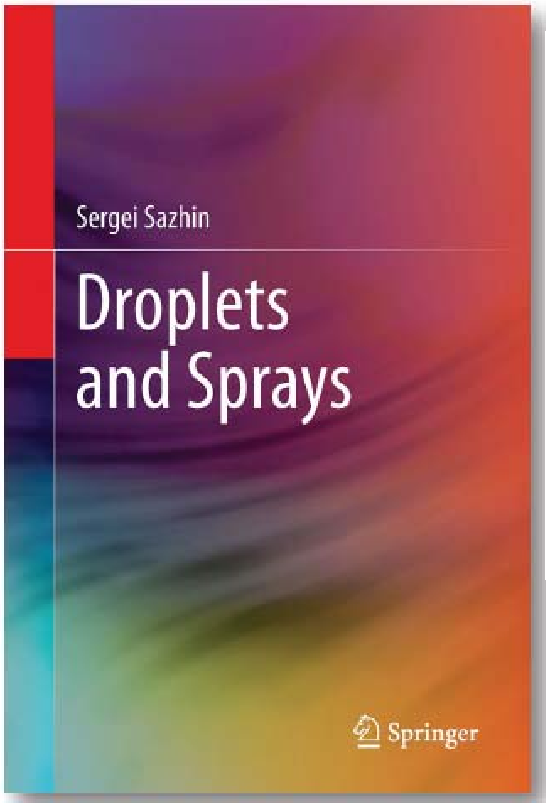
Preliminary results (film)



Preliminary results (film)



Challenges referring to spray modelling



Fuel 196 (2017) 69–101

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Review article

Modelling of fuel droplet heating and evaporation: Recent results and unsolved problems

Sergei S. Sazhin

Sir Harry Ricardo Laboratories, Advanced Engineering Centre, School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, UK

Acknowledgements

The authors are grateful to the EPSRC (grants EP/K005758/1 and EP/M002608/1) for their financial support.

Thank you for your attention

Modelling Of Spray and Film Drying: Preliminary Results

S.S. Sazhin and *O. Rybdylova*

The Sir Harry Ricardo Laboratories, School of Computing, Engineering and Mathematics,
University of Brighton, UK

EPSRC Engineering and Physical Sciences Research Council

University of Brighton