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Modelling of micro-explosions: simple solutions to complex problems

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RSF Russian Science Foundation

Plan

Background and motivation

Micro-explosions (simple analytical model)

Micro-explosions (simple numerical model)

Effect of the nucleation temperature

Effects of support, convection and thermal radiation

‘Grouping’ effects

Effect of multi-component composite droplets

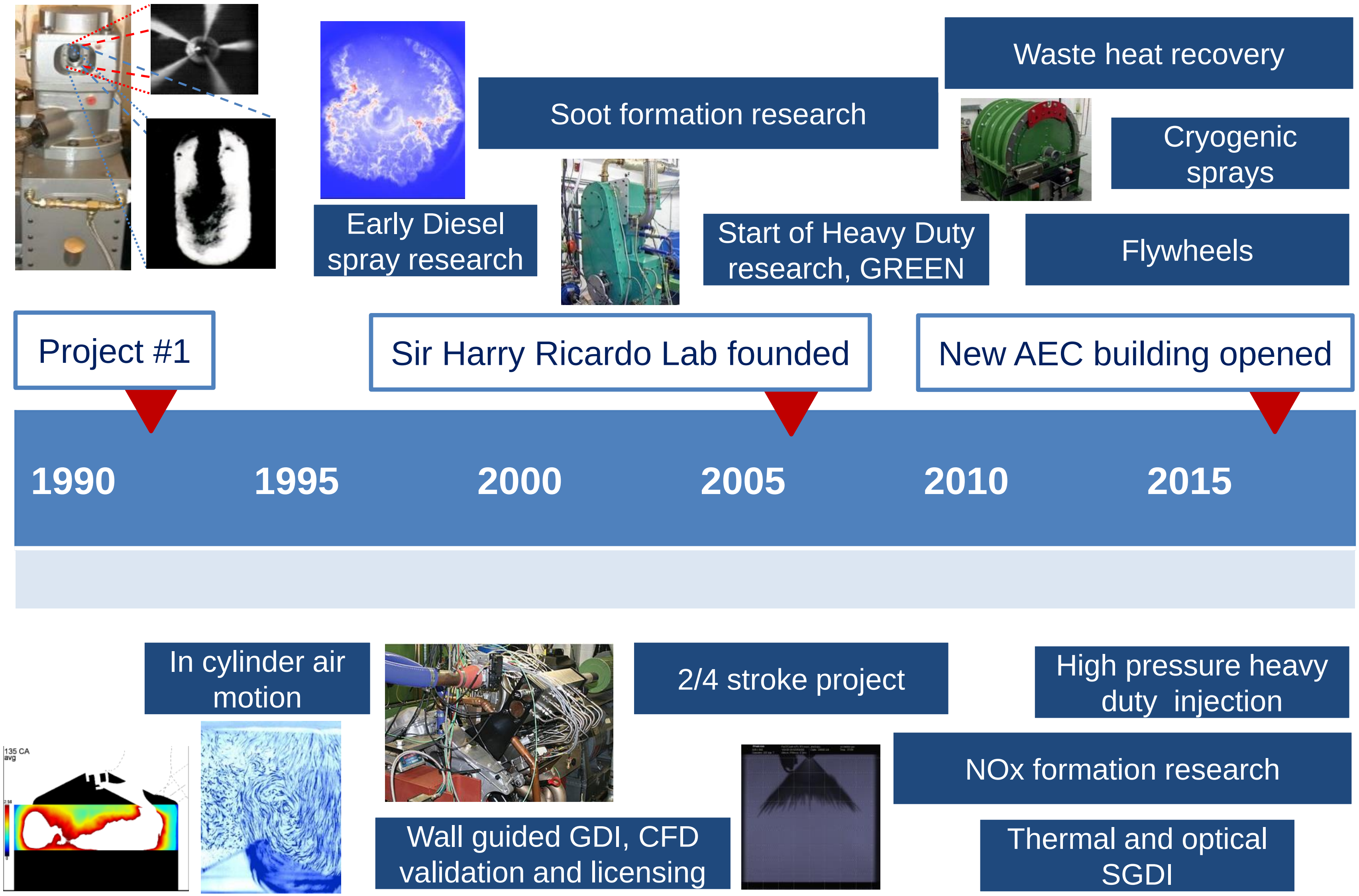
Most recent results

University of Brighton

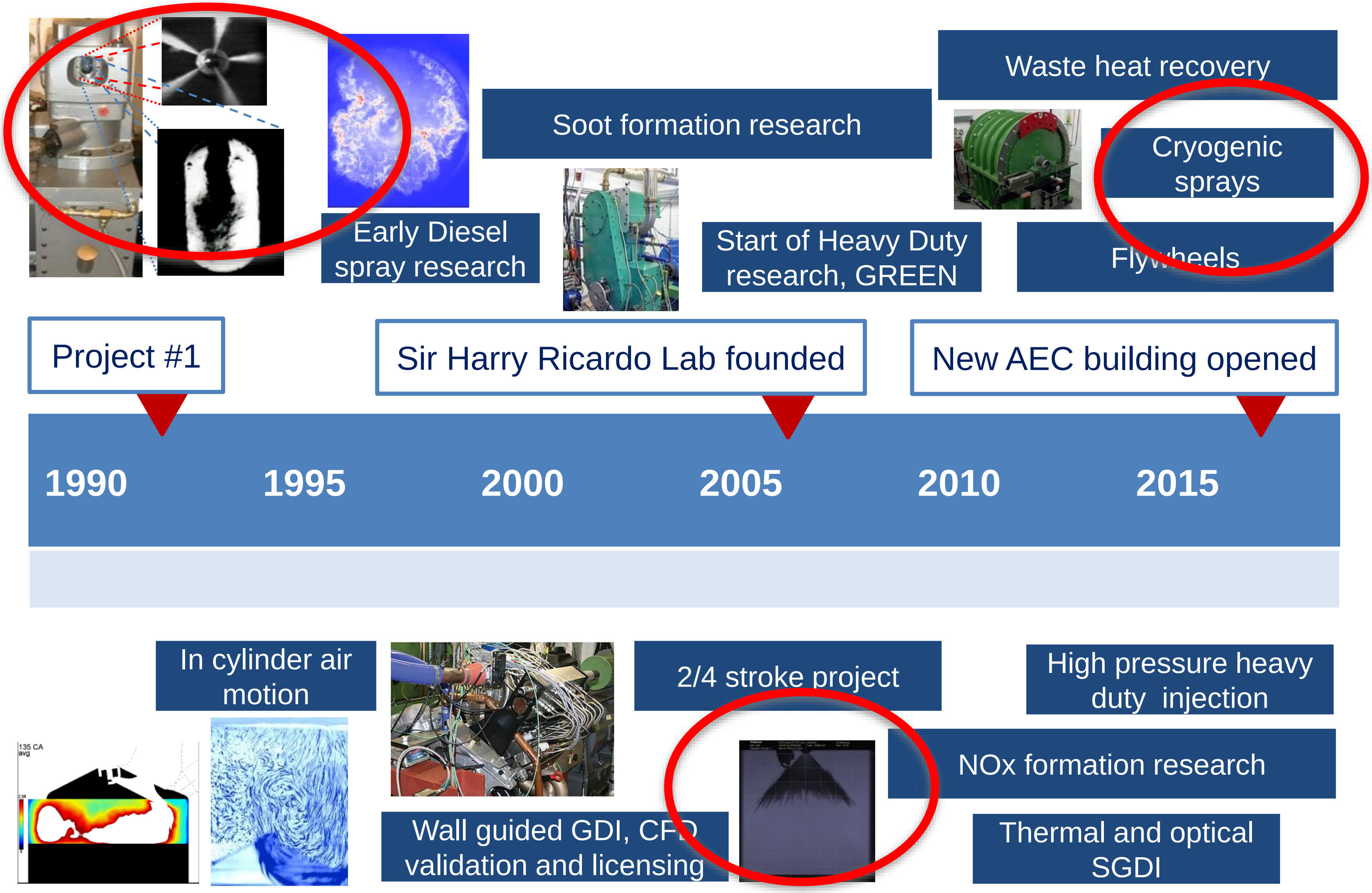
Advanced Engineering Centre

Background

Advanced Engineering Centre

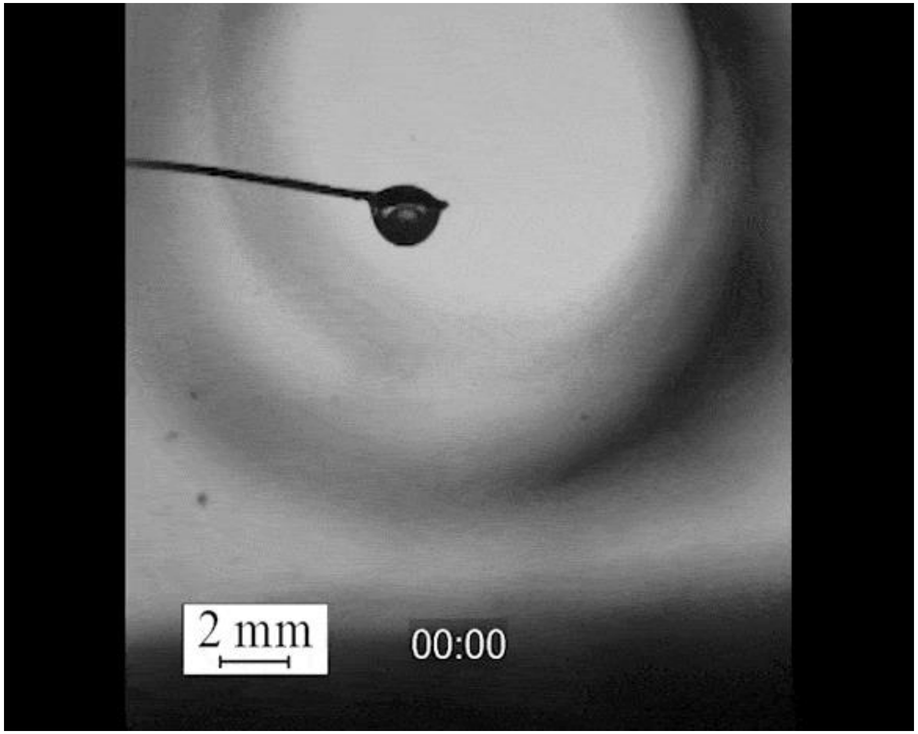


Advanced Engineering Centre

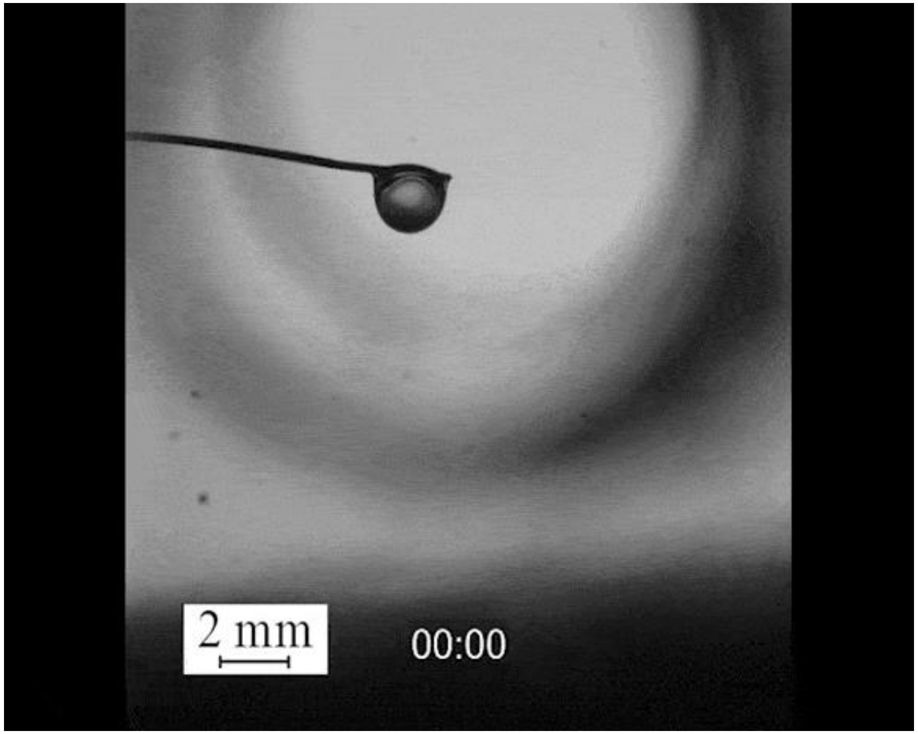


Phenomena: water sub-droplet inside a fuel droplet

Puffing



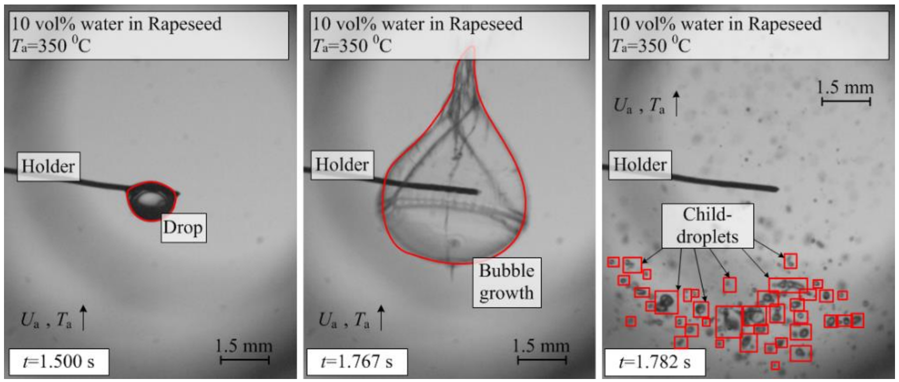
Micro-explosion



Video clips showing the development of puffing/micro-explosion in multi-component droplets

Motivation

Puffing/micro-explosion lead to the reduction of exhaust emissions while improving characteristics of Diesel engine performance without any constructed modification.

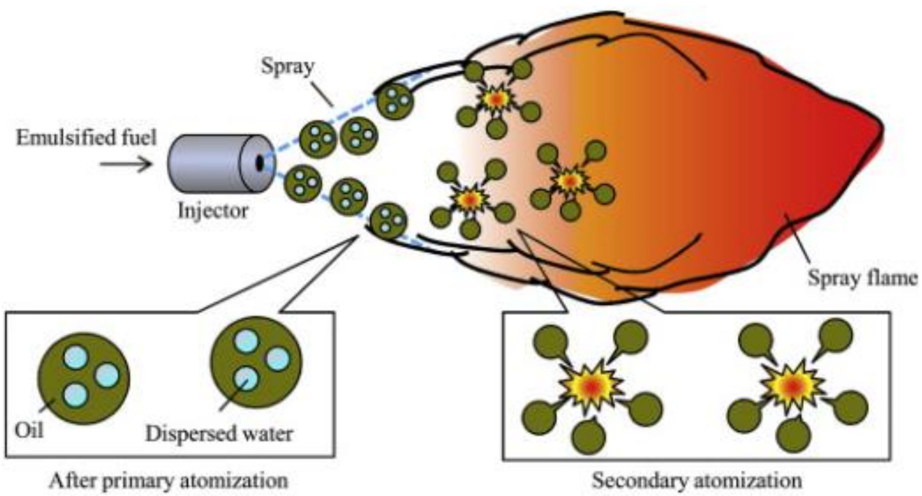


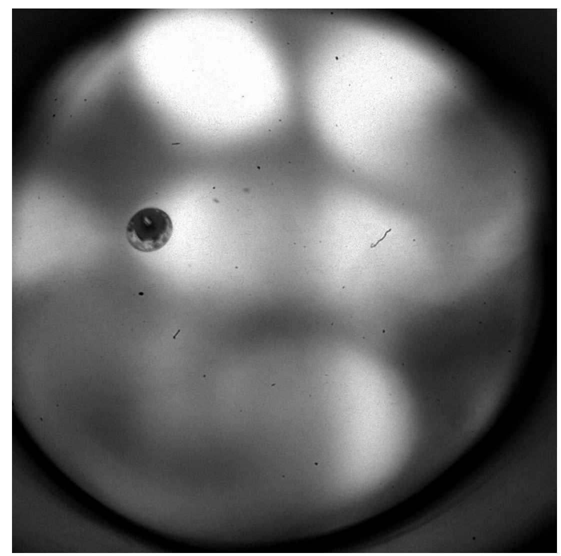
Reducing anthropogenic emissions NOx, SOx > 20%

Rapid increase in the liquid fuel surface area in 10-100 times

Saving fuel > 2%

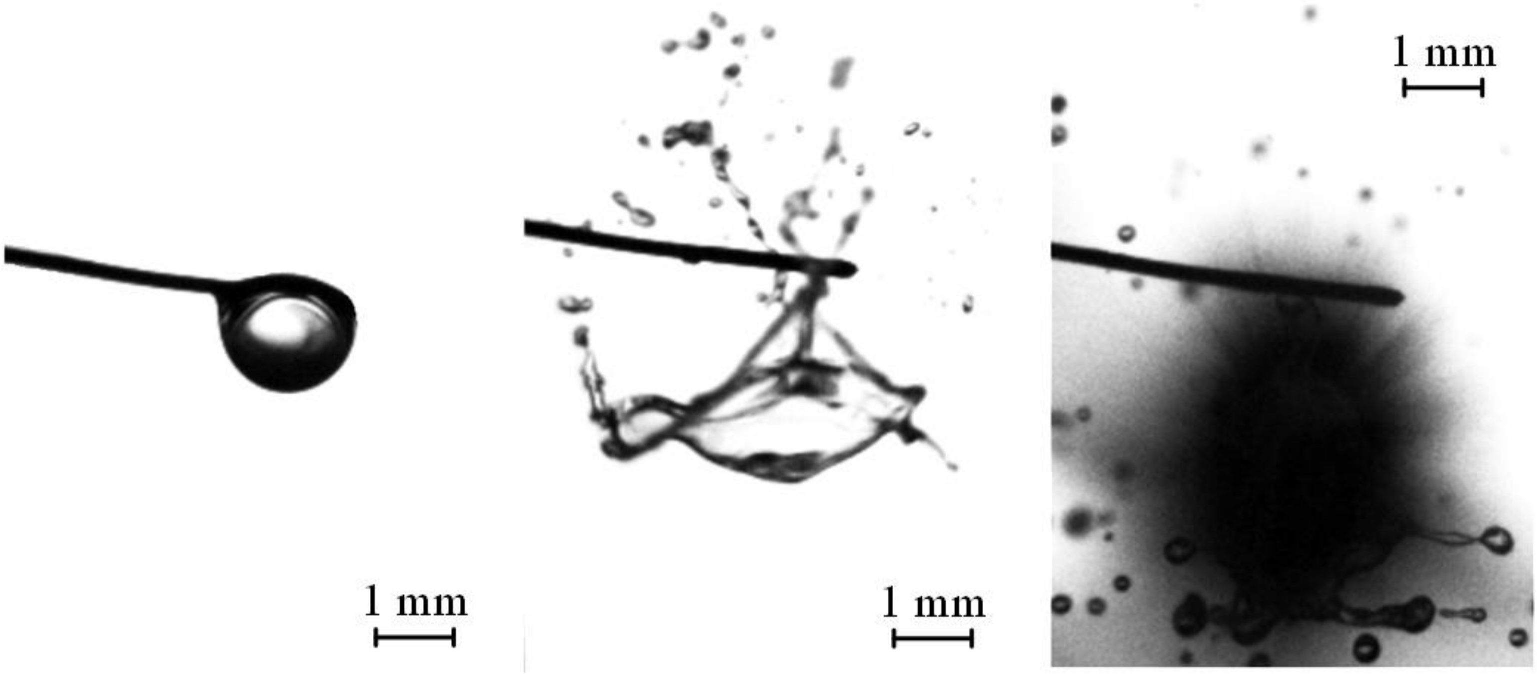
*





* H. Watanabe, Y. Suzuki, T. Harada, Y. Matsushita, H. Aoki, T. Miura, An experimental investigation of the breakup characteristics of secondary atomization of emulsified fuel droplet, *Energy*. 2010. V. 35. P. 806-813.

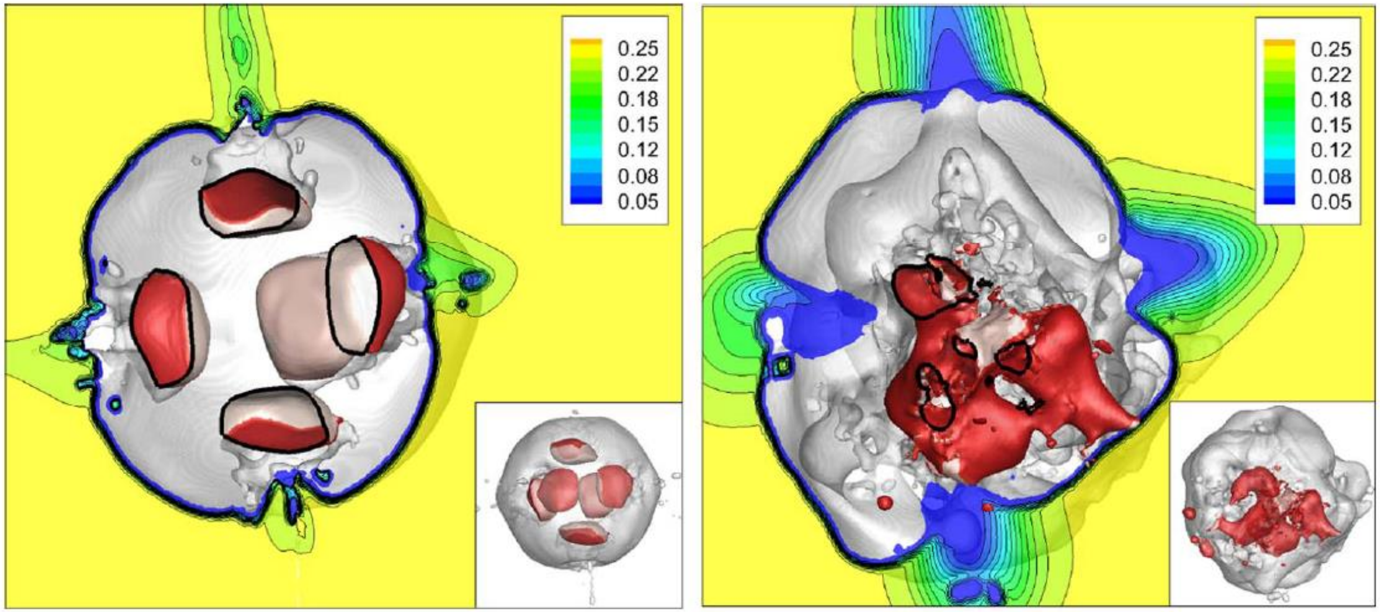
Experiments



$t = 0.500$ s $t = 0.671$ s $t = 0.675$ s

Typical dynamics of the puffing/micro-explosion in the experiments performed at National Research Tomsk Polytechnic University (Diesel (90%)+water(10%))

Modelling



(a) (b)

FIG. 17. Microexplosion induced by multiple puffing in Case C3-3D. (a) $t = 1.0\ \mu s$ and (b) $t = 3.0\ \mu s$. See Fig. 7 for explanation of contour colors and legends.

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PHYSICS OF FLUIDS **26**, 103302 (2014)

Physics of puffing and microexplosion of emulsion fuel droplets

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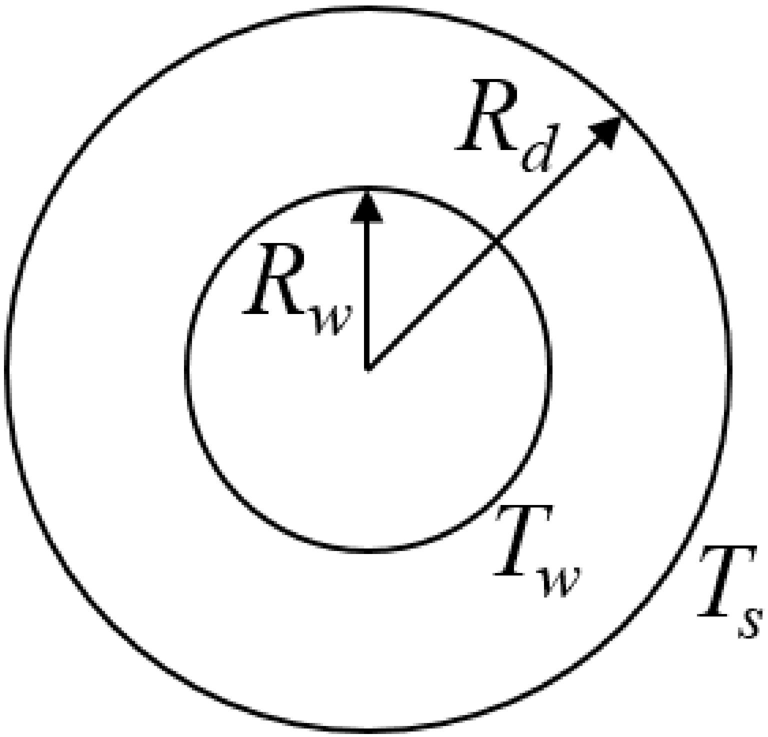
Micro-explosions (simple analytical model)

Assumptions



Basic equations and approximations

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

where

$$\kappa = \begin{cases} \kappa_w = k_w/(c_w \rho_w) & \text{when} \quad R \le R_w \\ \kappa_f = k_f/(c_f \rho_f) & \text{when} \quad R_w < R \le R_d, \end{cases}$$

$$T|_{t=0} = \begin{cases} T_{w0}(R) & \text{when} \quad R \le R_w \\ T_{f0}(R) & \text{when} \quad R_w < R \le R_d, \end{cases}$$

$$T|_{R=R_w^-} = T|_{R=R_w^+}, \qquad k_w \left. \frac{\partial T}{\partial R} \right|_{R=R_w^-} = k_f \left. \frac{\partial T}{\partial R} \right|_{R=R_w^+},$$

$$h\left(T_g - T(R_d)\right) = k_f \left. \frac{\partial T}{\partial R} \right|_{R=R_d-0},$$

$$T_{w0}(R_w) = T_{f0}(R_w)$$

Boundary condition

$$h\left(T_g - T(R_d)\right) = k_f \left.\frac{\partial T}{\partial R}\right|_{R=R_d-0}$$

$$T(R_d) \equiv T_s = T_g - \frac{k_f}{h} \left.\frac{\partial T}{\partial R}\right|_{R=R_d-0}$$

$$T(R_d) \equiv T_s$$

The equation was solved analytically

Assumptions

- The temperature of the droplet surface is assumed to be constant during the whole period of droplet heating (not just during individual time steps).

- The effects of droplet evaporation and swelling can be ignored.

- All thermodynamic and transport properties (liquid thermal conductivities, heat capacities and densities) can be set at the initial droplet temperature.

- Micro-explosion starts when $T_w = T_B$ (the boiling temperature of water)

Analytical solution

$$T(R,t) = T_s + \frac{1}{R}\sum_{n=1}^{\infty}\left[\exp\left(-\lambda_n^2 t\right)\left(\Theta_{n1}+\Theta_{n2}\right) + \int_0^t \exp\left(-\lambda_n^2\left(t-\tau\right)\right) p_n(\tau)\mathrm{d}\tau\right] v_n(R), \tag{8}$$

where

$$\Theta_{n1} = \frac{T_0 c_w \rho_w}{||v_n||^2\left(\lambda_n a_w\right)^2}\left[\lambda_n a_w R_w \cot\left(\lambda_n a_w R_w\right) - 1\right], \tag{9}$$

$$\Theta_{n2} = \frac{T_0 c_f \rho_f}{||v_n||^2\left(\lambda_n a_f\right)^2}\left[\lambda_n a_f R_w \cot\left(\lambda_n a_f\left(R_d - R_w\right)\right) - \frac{\lambda_n a_f R_d}{\sin\left(\lambda_n a_f\left(R_d - R_w\right)\right)} + 1\right], \tag{10}$$

$$T_0 = T_s - T_{w0} = T_s - T_{f0} \tag{11}$$

Analytical solution

$$T(R,t) = T_s + \frac{1}{R}\sum_{n=1}^{\infty}\left[\exp\left(-\lambda_n^2 t\right)\left(\Theta_{n1}+\Theta_{n2}\right) + \int_0^t \exp\left(-\lambda_n^2\left(t-\tau\right)\right) p_n(\tau)\mathrm{d}\tau\right] v_n(R), \tag{8}$$

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$$\Theta_{n1} = \frac{T_0 c_w \rho_w}{||v_n||^2\left(\lambda_n a_w\right)^2}\left[\lambda_n a_w R_w \cot\left(\lambda_n a_w R_w\right) - 1\right], \tag{9}$$

$$\Theta_{n2} = \frac{T_0 c_f \rho_f}{||v_n||^2\left(\lambda_n a_f\right)^2}\left[\lambda_n a_f R_w \cot\left(\lambda_n a_f\left(R_d - R_w\right)\right) - \frac{\lambda_n a_f R_d}{\sin\left(\lambda_n a_f\left(R_d - R_w\right)\right)} + 1\right], \tag{10}$$

$$T_0 = T_s - T_{w0} = T_s - T_{f0} \tag{11}$$

$$v_n(R) = \begin{cases} \pm\frac{\sin(\lambda_n a_w R)}{\sin(\lambda_n a_w R_w)} & \text{when} \quad R < R_w \\ \pm\frac{\sin(\lambda_n a_f (R - R_d))}{\sin(\lambda_n a_f (R_w - R_d))} & \text{when} \quad R_w \le R \le R_d, \end{cases}$$

$$||v_n||^2 = \frac{c_w \rho_w R_w}{2\sin^2(\lambda_n a_w R_w)} + \frac{c_f \rho_f (R_d - R_w)}{2\sin^2(\lambda_n a_f (R_w - R_d))} - \frac{k_w - k_f}{2 R_w \lambda_n^2},$$

$$p_n(t) = \frac{c_w \rho_w}{||v_n||^2}\int_0^{R_w} R P(t,R) v_n(R) \mathrm{d}R.$$

A countable set of positive eigenvalues λ_n is found from the solution to the equation:

$$\sqrt{k_w c_w \rho_w}\cot(\lambda a_w R_w) - \sqrt{k_f c_f \rho_f}\cot(\lambda a_f (R_w - R_d)) = \frac{k_w - k_f}{R_w \lambda}.$$

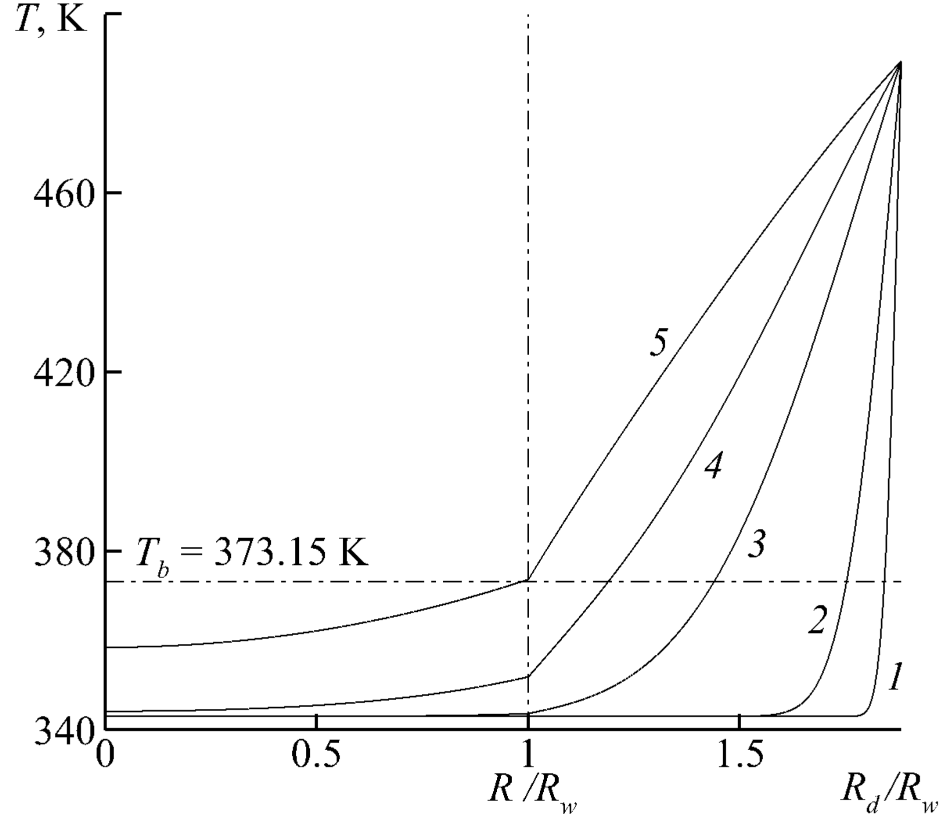
These are arranged in ascending order $0 < \lambda_1 < \lambda_2 < \ldots.$. $a_w = \sqrt{\frac{c_w \rho_w}{k_w}}$, $a_f = \sqrt{\frac{c_f \rho_f}{k_f}}$.

Results

Table 1: Droplet and gas properties.

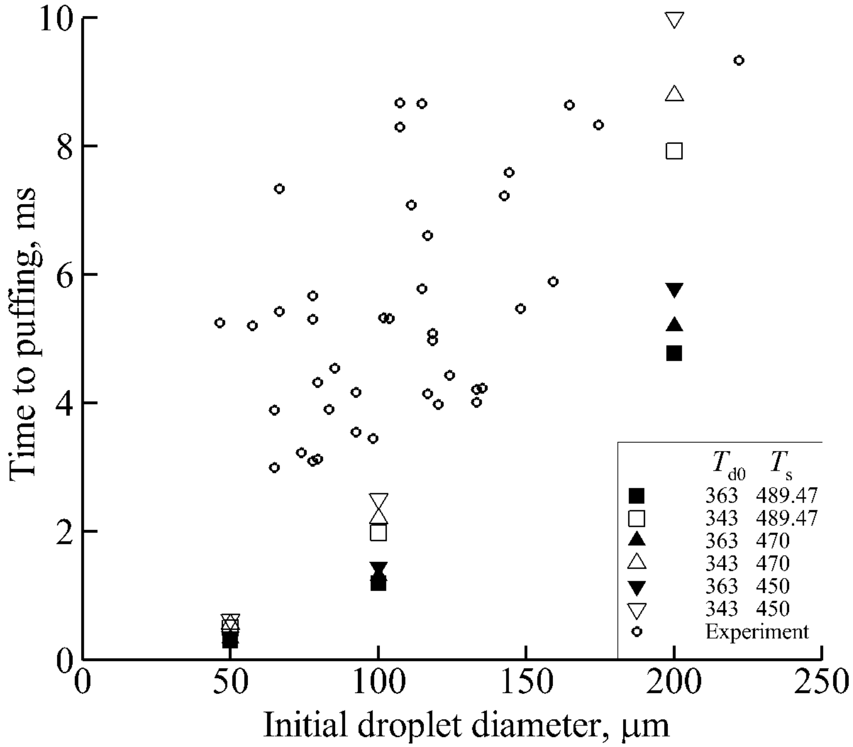
Parameter	Value
Parent droplet radii (R_d) [μm]	25; 50; 100
Droplet initial composition [vol]	0.15 water + 0.85 n-dodecane
n-dodecane density (ρ_f) [kg/m^3]	825
Gas composition	air
Droplet surface temperatures (T_s) [K]	489.47 (boiling temperature), 470, 450
Initial droplet temperature (T_d0) [K]	343 and 363
Gas (air) pressure [MPa]	0.1

Results



The plots predicted by the new model of temperatures inside the composite droplet (*T*) versus normalised distance from the droplet centre R/R_w at 5 instants of time: 1.1 µs (curve 1), 11 µs (curve 2), 0.11 ms (curve 3), 0.25 ms (curve 4) and 0.5 ms (curve 5).

Results



The values of time to puffing, predicted by the new model, versus the initial droplet diameters for two values of the initial droplet temperature and three values of droplet surface temperature (see the insert in this figure). The experimentally observed values of this time are shown as empty circles.

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A simple model for puffing/micro-explosions in water-fuel emulsion droplets

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Micro-explosions (simple numerical model)

Simple numerical model

Assumptions:

The temperature of the droplet surface is assumed to be constant during the whole period of droplet heating (not just during individual time steps).

The surface temperature is allowed to vary with time (the Robin boundary condition is used)

The effects of droplet evaporation and swelling can be ignored.

The effects of droplet evaporation and swelling are taken into account

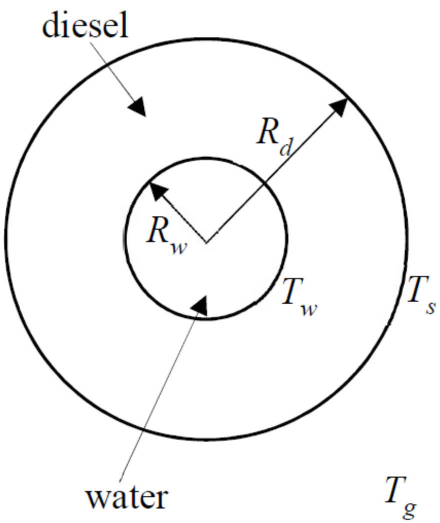
All thermodynamic and transport properties (liquid thermal conductivities, heat capacities and densities) can be set at the initial droplet temperature.

The temperature and time dependence of thermodynamic and transport properties are taken into account

Micro-explosion starts when $T_w = T_B$ (the boiling temperature of water)

Micro-explosion starts when $T_w = T_N$ (the nucleation temperature of water)

Simple numerical model



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

$$\kappa = \begin{cases} \kappa_w = \dfrac{k_w}{c_w \cdot \rho_w} & \text{when } R \leq R_w \\ \kappa_f = \dfrac{k_f}{c_f \cdot \rho_f} & \text{when } R_w < R \leq R_d \end{cases}$$

$$T|_{t=0} = \begin{cases} T_{w0}(R) & \text{when } R \leq R_w \\ T_{f0}(R) & \text{when } R_w < R \leq R_d, \end{cases}$$

$$T|_{R=R_w^-} = T|_{R=R_w^+} \quad ; \quad k_w \frac{\partial T}{\partial R}\bigg|_{R=R_w^-} = k_f \frac{\partial T}{\partial R}\bigg|_{R=R_w^+}$$

Simple numerical model

$$\left(k_f \frac{\partial T}{\partial R} + h \cdot T\right)\Big|_{R=R_d^-} = h \cdot T_g + \rho_{lf} \cdot L_f \cdot \dot{R}_d,$$

$$\dot{m}_d = -4\pi R_d D_v \rho_{\text{total}} \ln\left(1 + B_M\right)$$

$$B_M = \left(Y_{vs} - Y_{v\infty}\right) / \left(1 - Y_{vs}\right)$$

$$\text{Nu} = 2\frac{\ln(1 + B_T)}{B_T}$$

Simple numerical model

$$T = \frac{1}{R_d \xi}\left[\sum_{n=1}^{\infty} \Theta_n(t) v_n(\xi) + \frac{\mu_0 \xi}{1+h_0}\right],$$

where

$$\Theta_n(t) = (q_n + f_n \mu_0)\exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right) + \frac{p_n}{\lambda_n^2}\left[1 - \exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right)\right],$$

$$\begin{aligned}
f_n &= \frac{1}{||v_n||^2}\int_0^1 f(\xi) v_n(\xi) b \mathrm{d}\xi \\
&= \frac{1}{||v_n||^2}\left\{\int_0^{\xi_w} \frac{-\xi}{1+h_0}\frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)} k_w a_w^2 \mathrm{d}\xi \right.\\
&\quad \left. + \int_{\xi_w}^1 \frac{-\xi}{1+h_0}\frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)} k_f a_f^2 \mathrm{d}\xi \right\}\\
q_n &= \frac{1}{||v_n||^2}\int_0^1 F_0(\xi) v_n(\xi) b \mathrm{d}\xi \\
&= \frac{1}{||v_n||^2}\left\{\int_0^{\xi_w} R_d \xi T_0(R_d \xi)\frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)} k_w a_w^2 \mathrm{d}\xi \right.\\
&\quad \left. + \int_{\xi_w}^1 R_d \xi T_0(R_d \xi)\frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)} k_f a_f^2 \mathrm{d}\xi \right\}\\
p_n &= \frac{1}{||v_n||^2}\int_0^1 R_d^3 \xi \tilde{P}(\xi) v_n(\xi) b \mathrm{d}\xi \\
&= \frac{1}{||v_n||^2}\left\{\int_0^{\xi_w} R_d^3 \xi \tilde{P}(\xi)\frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)} k_w a_w^2 \mathrm{d}\xi \right.\\
&\quad \left. + \int_{\xi_w}^1 R_d^3 \xi \tilde{P}(\xi)\frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)} k_f a_f^2 \mathrm{d}\xi \right\}
\end{aligned}$$

Simple numerical model

$$T = \frac{1}{R_d \xi}\left[\sum_{n=1}^{\infty}\Theta_n(t)v_n(\xi) + \frac{\mu_0 \xi}{1+h_0}\right],$$

where

$$\Theta_n(t) = (q_n + f_n\mu_0)\exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right) + \frac{p_n}{\lambda_n^2}\left[1 - \exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right)\right],$$

$$\begin{aligned} f_n &= \frac{1}{||v_n||^2}\int_0^1 f(\xi)v_n(\xi)b\mathrm{d}\xi \\ &= \frac{1}{||v_n||^2}\left\{\int_0^{\xi_w}\frac{-\xi}{1+h_0}\frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)}k_w a_w^2 \mathrm{d}\xi \right. \\ &\quad \left. + \int_{\xi_w}^1 \frac{-\xi}{1+h_0}\frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)}k_f a_f^2 \mathrm{d}\xi\right\} \\ q_n &= \frac{1}{||v_n||^2}\int_0^1 F_0(\xi)v_n(\xi)b\mathrm{d}\xi \\ &= \frac{1}{||v_n||^2}\left\{\int_0^{\xi_w} R_d\xi T_0(R_d\xi)\frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)}k_w a_w^2 \mathrm{d}\xi \right. \\ &\quad \left. + \int_{\xi_w}^1 R_d\xi T_0(R_d\xi)\frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)}k_f a_f^2 \mathrm{d}\xi\right\} \\ p_n &= \frac{1}{||v_n||^2}\int_0^1 R_d^3\xi \tilde{P}(\xi)v_n(\xi)b\mathrm{d}\xi \\ &= \frac{1}{||v_n||^2}\left\{\int_0^{\xi_w} R_d^3\xi \tilde{P}(\xi)\frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)}k_w a_w^2 \mathrm{d}\xi \right. \\ &\quad \left. + \int_{\xi_w}^1 R_d^3\xi \tilde{P}(\xi)\frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)}k_f a_f^2 \mathrm{d}\xi\right\} \end{aligned}$$

$$H = \frac{h}{k_f} - \frac{1}{R_d}, \quad \mu = \frac{R_d}{k_f}\left(hT_g + \rho_l L_f \dot{R}_d\right), \quad \xi = R/R_d, \quad \tilde{P}(\xi) = P(\xi R_d),$$

$$F(t,\xi) = u(t,R) \equiv T(R,t)R, \quad h_0 = HR_d = \frac{hR_d}{k_f} - 1,$$

$$\mu_0 = \mu R_d = \frac{R_d^2}{k_f}\left(hT_g + \rho_l L_f \dot{R}_d\right) = \frac{R_d^2 h T_{\mathrm{eff}}}{k_f}.$$

$$f(\xi) \equiv \frac{-\xi}{1+h_0} = \sum_{n=1}^{\infty} f_n(t)v_n(\xi),$$

$$F_0(\xi) \equiv R_d\xi T_0(R_d\xi) = \sum_{n=1}^{\infty} q_n(t)v_n(\xi), \quad R_d^3\xi\tilde{P}(\xi) = \sum_{n=1}^{\infty} p_n(t)v_n(\xi)$$

$$v_n(\xi) = \begin{cases} \dfrac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)} & \text{when} \quad 0 \le \xi \le \xi_w \\[2ex] \dfrac{\sin\left(\lambda_n a_f \xi + \beta_n\right)}{\sin\left(\lambda_n a_f \xi_w + \beta_n\right)} & \text{when} \quad \xi_w < \xi \le 1, \end{cases}$$

β_n is $\beta(\lambda = \lambda_n)$,

$$\begin{aligned} ||v_n||^2 = \int_0^1 v_n^2 b\mathrm{d}\xi &= \frac{\sqrt{c_w\rho_w k_w}}{\lambda_n \sin^2(\lambda_n a_w \xi_w)}\left[\frac{a_w\lambda_n\xi_w}{2} - \frac{\sin(2a_w\lambda_n\xi_w)}{4}\right] \\ &+ \frac{\sqrt{c_f\rho_f k_f}}{\lambda_n \sin^2(\lambda_n a_f \xi_w + \beta_n)}\left\{\frac{a_f\lambda_n(1-\xi_w)}{2}\right. \\ &\left. - \frac{\sin(2\lambda_n a_f + 2\beta_n) - \sin(2\lambda_n a_f \xi_w + 2\beta_n)}{4}\right\}, \end{aligned}$$

$$\beta = \cot^{-1}\left[\frac{k_f - k_w}{k_f a_f \xi_w \lambda} + \frac{k_w a_w}{k_f a_f}\cot(a_w\lambda\xi_w)\right] + i\pi - a_f\lambda\xi_w,$$

$i = 0, 1, 2, 3, \ldots,$ we restrict the analysis to the case when $i = 0$ (the values of v would be the same for other values of i), a countable set of positive eigenvalues λ_n is obtained from the boundary condition at $\xi = 1$:

$$\lambda_n a_f \cos(\lambda_n a_f + \beta) + h_0 \sin(\lambda_n a_f + \beta) = 0.$$

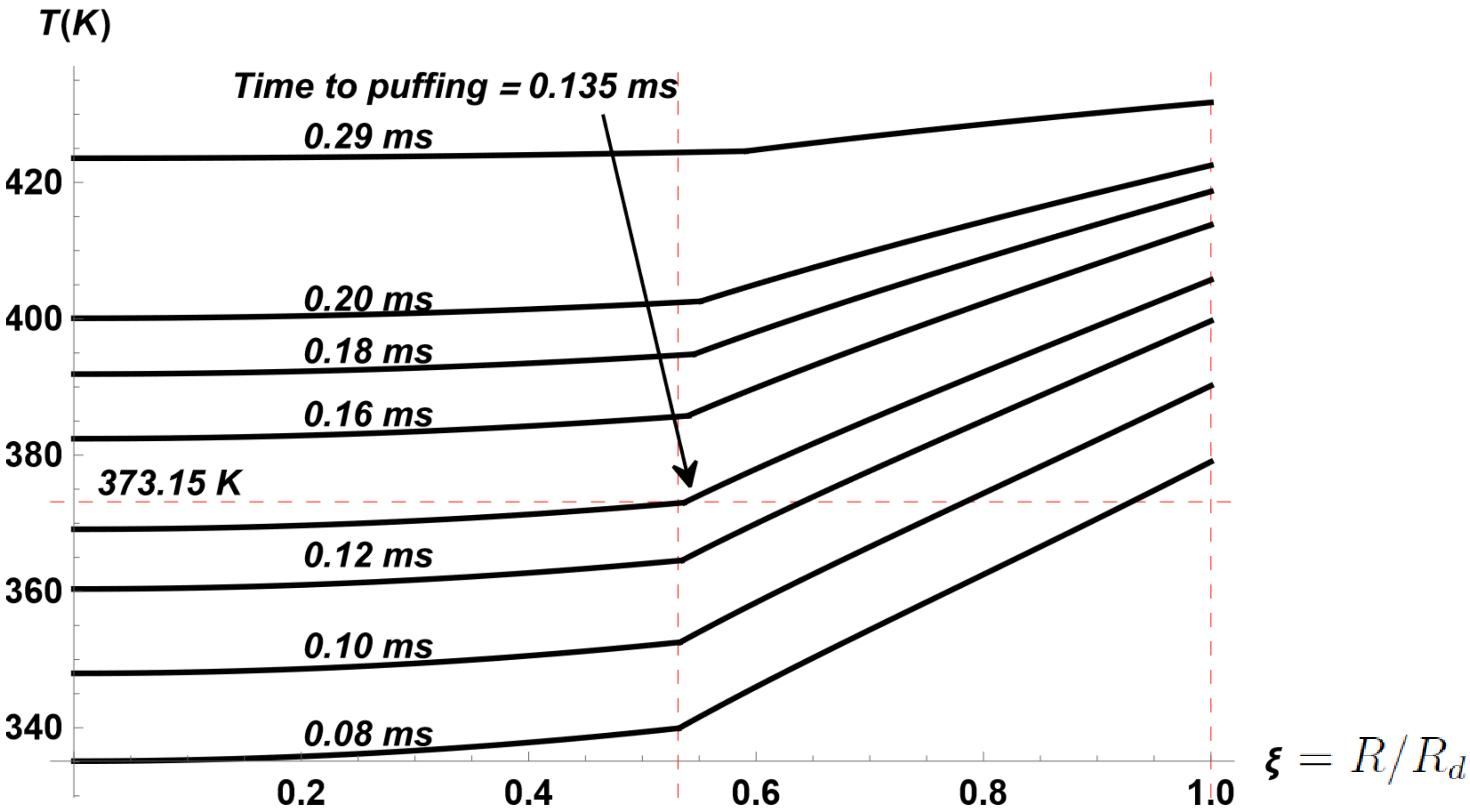
Simple numerical model

This solution was implemented into the numerical code and used at each time step of calculations. The dependence of all input parameters on temperature was taken into account. The effects of thermal swelling were taken into account based on the following expressions:

$$R_{w1} = R_{w0}\left(\frac{\rho_{w0}}{\rho_{w1}}\right)^{1/3}$$

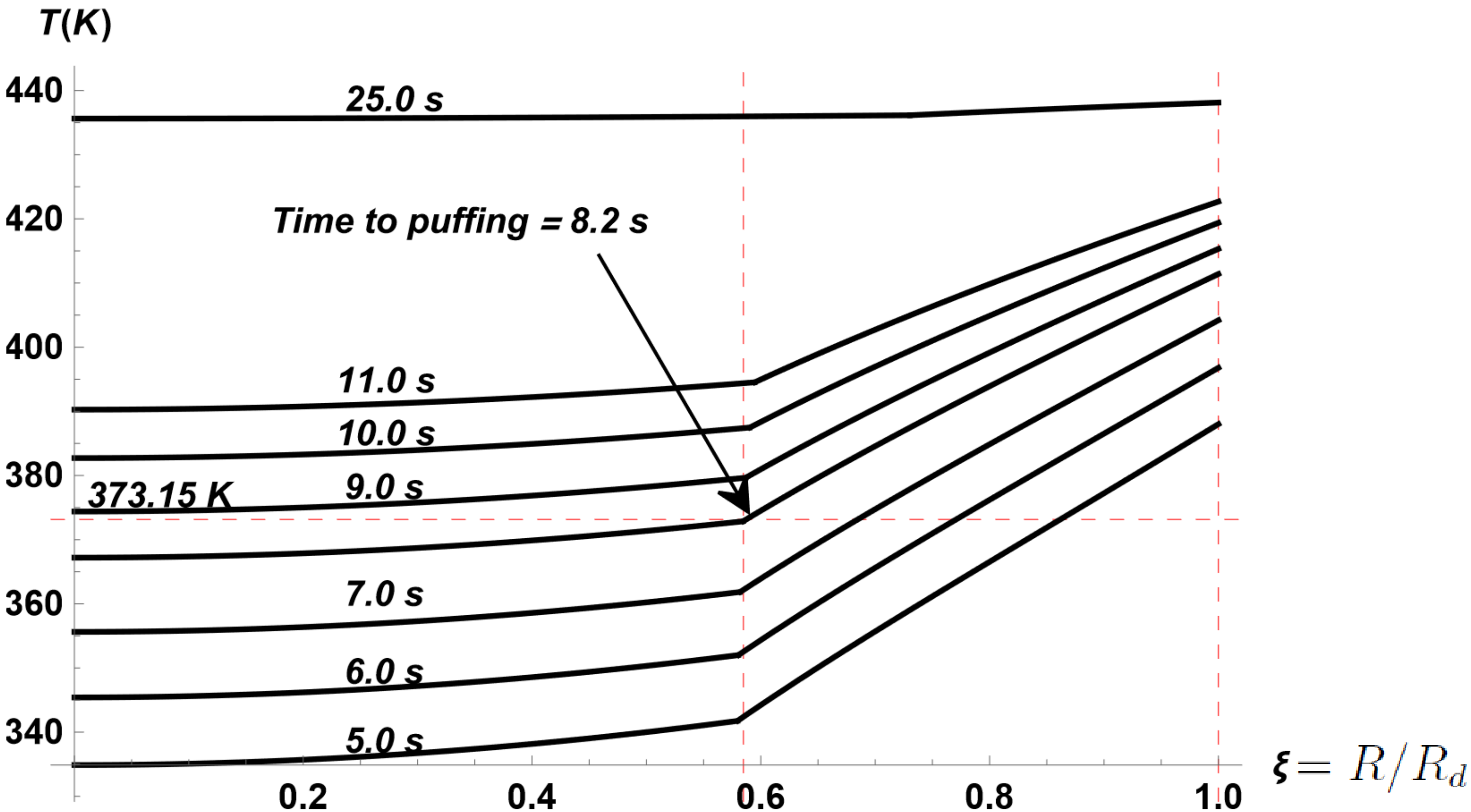
$$\Delta R_{d(s)} \equiv R_{d1} - R_{d0} = R_{d0}\left\{\left[\left(1 - \frac{R_{w0}^3}{R_{d0}^3}\right)\frac{\rho_{f0}}{\rho_{f1}} + \frac{R_{w0}^3}{R_{d0}^3}\frac{\rho_{w0}}{\rho_{w1}}\right]^{1/3} - 1\right\}$$

Simple numerical model



Plots of *T(ξ)* for n-dodecane/water droplets at several time instants for R_{d0} = 5 μm, T_{d0} = 300 K, T_g = 700 K, p = 1 atm = 101.325 kPa, V_{w0} = 15% .

Simple numerical model



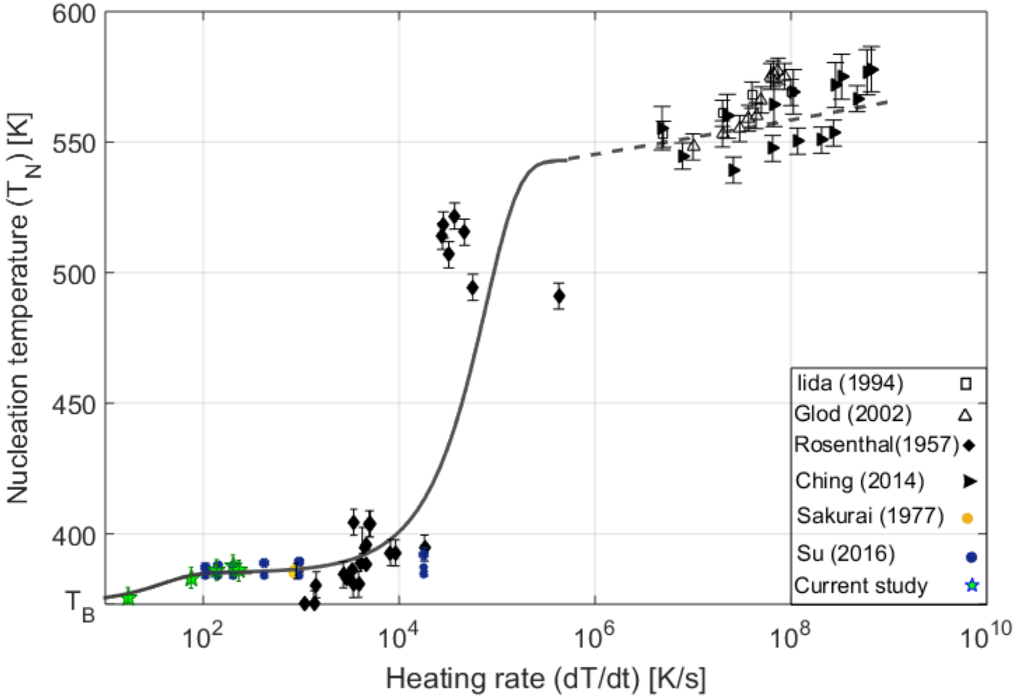
Plots of *T(ξ)* for n-dodecane/water droplets at several time instants for R_{d0} = 1330 μm, T_{d0} = 300 K, T_g = 773 K, *p* = 1 atm = 101.325 kPa, V_{w0} = 20% . The effects of swelling were taken into account

Effect of the nucleation temperature

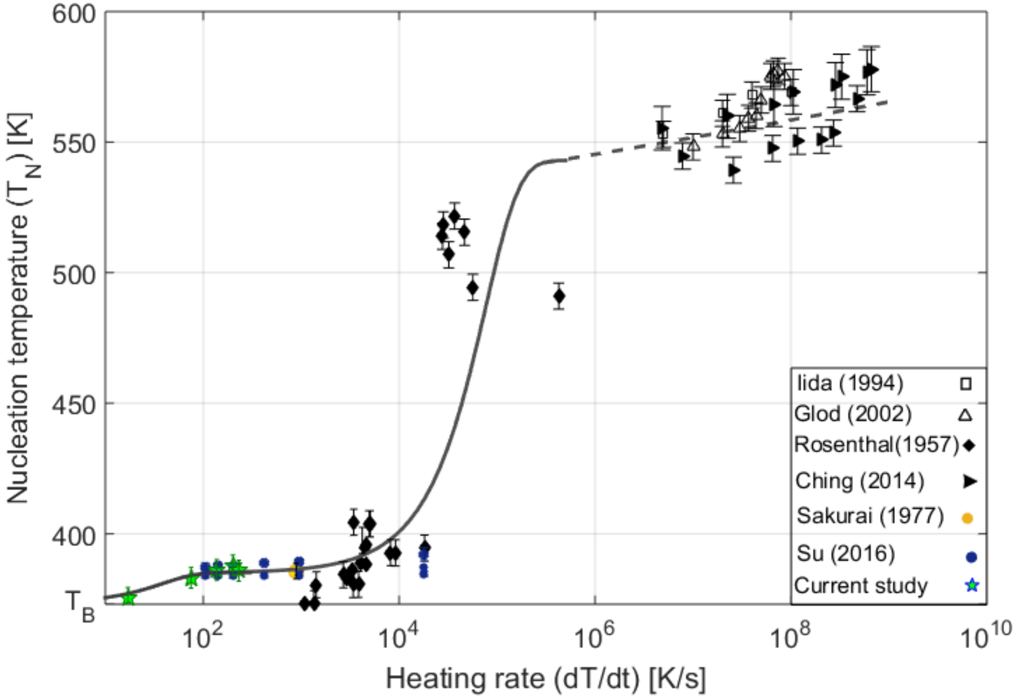
Effect of the nucleation temperature

We will relax our assumption that '**Puffing/micro-explosion starts when the temperature at the water/fuel interface reaches the water boiling temperature**'.

Effect of the nucleation temperature

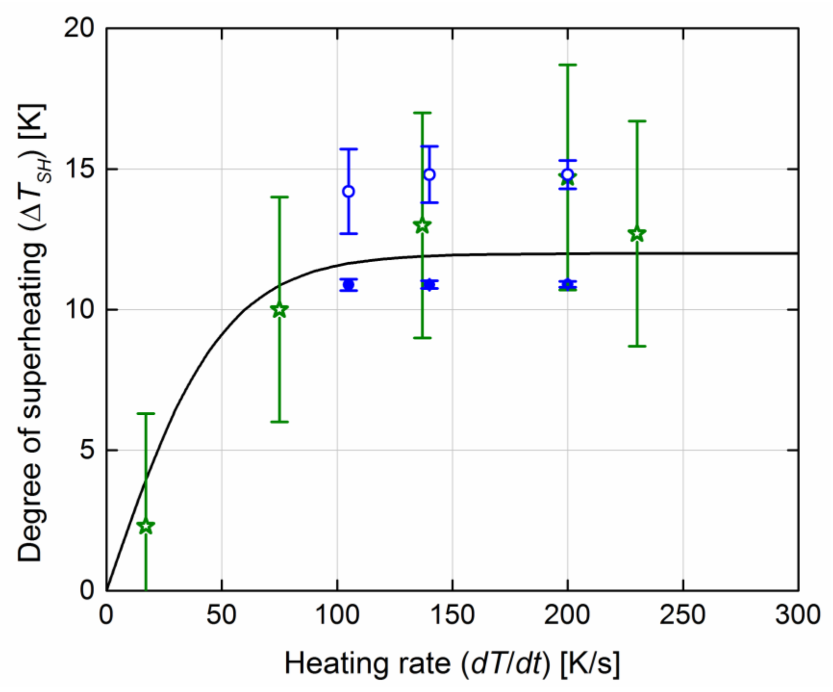


Effect of the nucleation temperature



$$T_N = 385 + 160 \times \tanh\left(\dot{T}/10^5\right) \qquad 10^2 \le \dot{T} \le 10^6 \;\; \mathrm{K/s}$$

Effect of the nucleation temperature



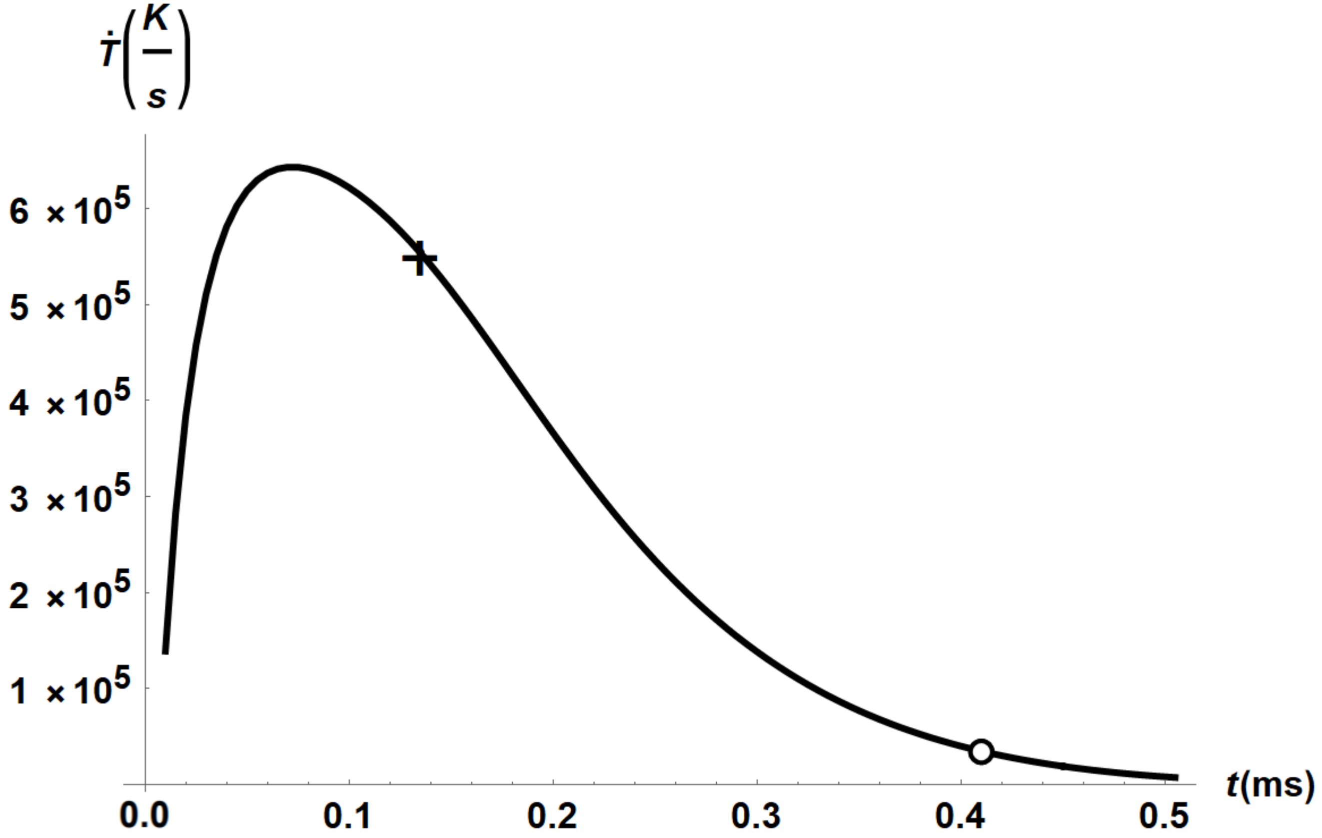
$$T_N = T_B + 12 \times \tanh(\dot{T}/50); \qquad 0 \leq \dot{T} \leq 300 \ \text{K/s}$$

Effect of the nucleation temperature

$$T_N = T_B + 12 \times \tanh(\dot{T}/50); \qquad 0 \le \dot{T} \le 300 \ \text{K/s}$$

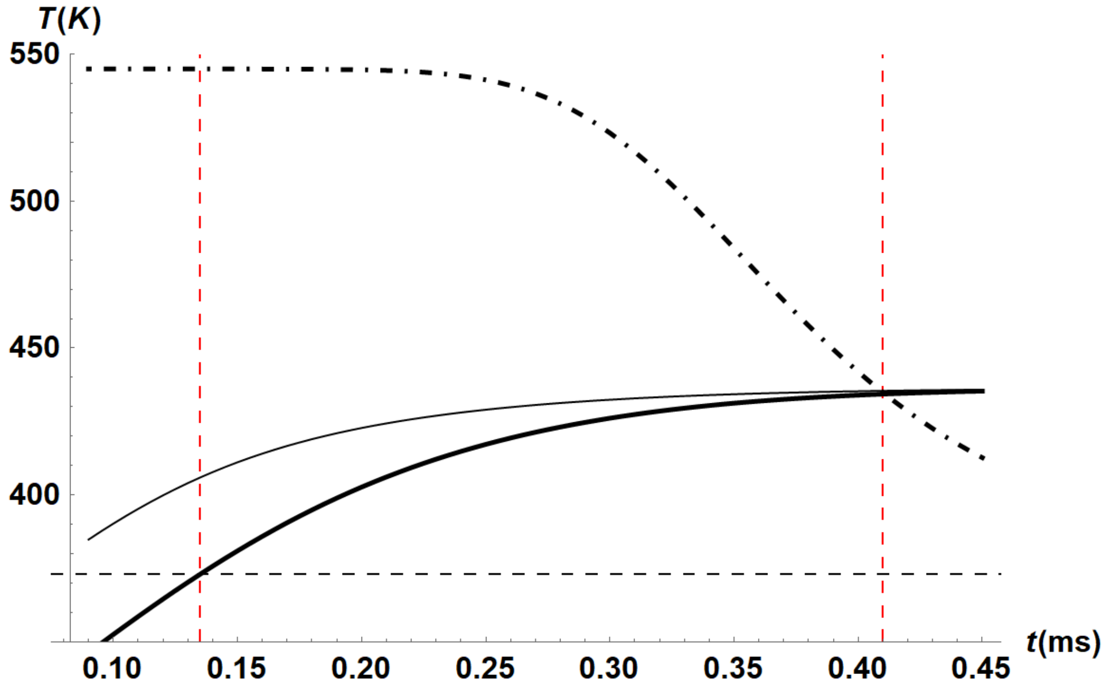
Both T_B and $\dot{T}$ are predicted by the analytical solution at each time step. Hence, the value of T_N can be obtained from the same solution using one of the correlations presented above

Effect of the nucleation temperature



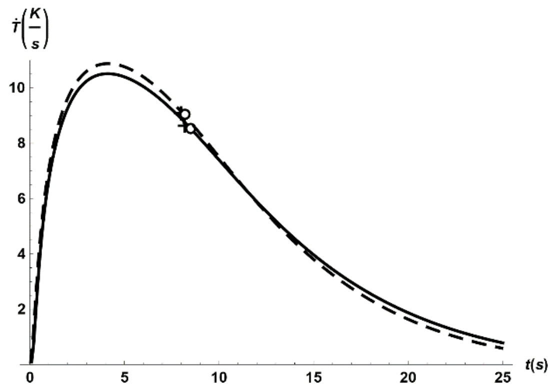
The plot of *dT/dt* at the water/fuel interface versus time, for for R_{d0} = 5 μm; the cross and circle indicate the time instant when $T_w = T_B$ and $T_w = T_N$, respectively.

Effect of the nucleation temperature

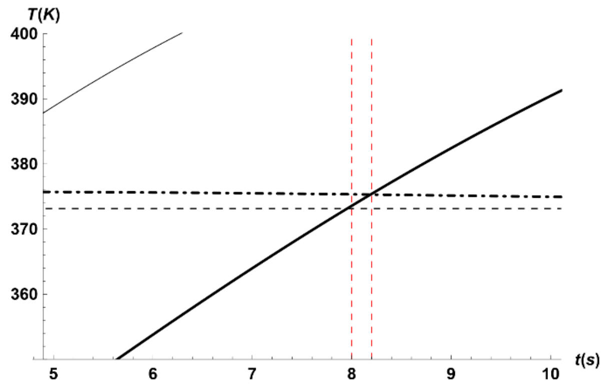


The plots of time evolution of T_W (thick solid), T_S (thin solid), T_N (dashed-dotted), and T_B (horizontal dashed line); the vertical dashed lines show the time instants when $T_W = T_B$ and $T_W = T_N$; the calculations were performed for the same values of parameters as in the previous figure.

Effect of the nucleation temperature



R_{d0} = 1330 μm



Simple numerical model

International Journal of Heat and Mass Transfer 161 (2020) 120238

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

ELSEVIER

A new approach to modelling micro-explosions in composite droplets

Check for updates

Sergei S. Sazhin[a,*], Tali Bar-Kohany[b,c], Zuhaib Nissar[d], Dmitrii Antonov[e], Pavel A. Strizhak[e], Oyuna D. Rybdylova[a]

Effect of support, convection and thermal radiation

Effect of support, convection and thermal radiation

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

$$T = \frac{1}{R_d \xi} \left[\sum_{n=1}^{\infty} \Theta_n(t) v_n(\xi) + \frac{\mu_0 \xi}{1 + h_0} \right],$$

where

$$\Theta_n(t) = (q_n + f_n \mu_0) \exp\left(-\frac{\lambda_n^2 t}{R_d^2} \right) + \frac{p_n}{\lambda_n^2} \left[1 - \exp\left(-\frac{\lambda_n^2 t}{R_d^2} \right) \right],$$

$$\begin{aligned} p_n &= \frac{1}{||v_n||^2} \int_0^1 R_d^3 \xi \tilde{P}(\xi) v_n(\xi) b \mathrm{d}\xi \\ &= \frac{1}{||v_n||^2} \left\{ \int_0^{\xi_w} R_d^3 \xi \tilde{P}(\xi) \frac{\sin(\lambda_n a_w \xi)}{\sin(\lambda_n a_w \xi_w)} k_w a_w^2 \mathrm{d}\xi \right. \\ &\quad \left. + \int_{\xi_w}^1 R_d^3 \xi \tilde{P}(\xi) \frac{\sin(\lambda_n a_f \xi + \beta_n)}{\sin(\lambda_n a_f \xi_w + \beta_n)} k_f a_f^2 \mathrm{d}\xi \right\} \end{aligned}$$

The effects of thermal radiation are included in the solution but have not been considered so far

$$\tilde{P}(\xi) = P(\xi R_d),$$

Effect of support

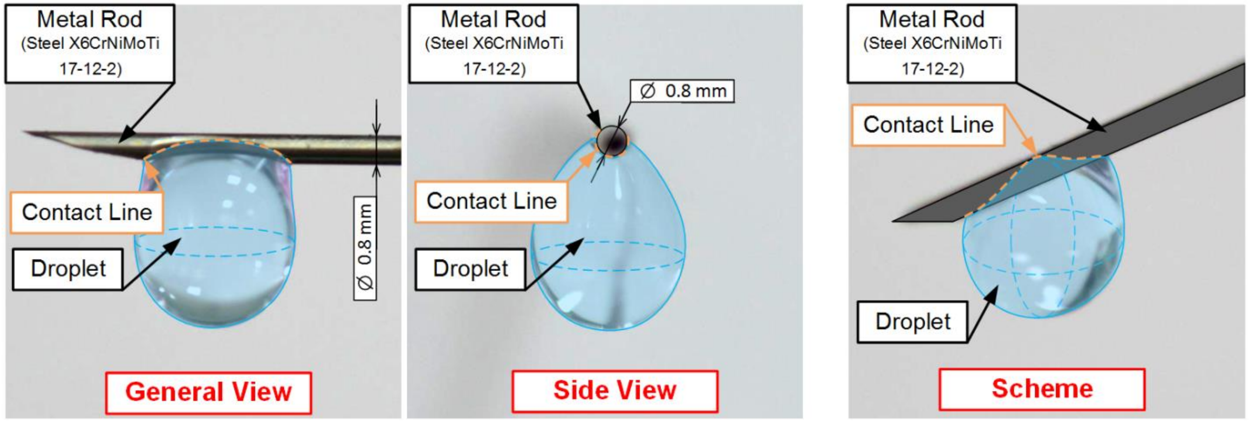
$$T=\frac{1}{R_d\xi}\left[\sum_{n=1}^{\infty}\Theta_n(t)\upsilon_n(\xi)+\frac{\mu_0\xi}{1+h_0}\right],$$

where

$$\Theta_n(t)=(q_n+f_n\mu_0)\exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right)+\frac{p_n}{\lambda_n^2}\left[1-\exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right)\right],$$

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

$$\tilde{P}(\xi)=P(\xi R_d).$$



Effect of support

$$q = \frac{k_w (T_{\sup} - T_c)}{R_d} S_c ,$$

heat supplied per unit droplet volume

$$q_v = \frac{3 k_w (T_{\sup} - T_c)}{4 \pi R_d^4} S_c$$

$$P(R) = \frac{3 k_w (T_{\sup} - T_c)}{4 \pi c_l \rho_l R_d^4} S_c$$

$S_c = \pi d_t R_d$, where d_t is the diameter of the thread, R_d is droplet radius

The effect of support is taken into account via the radiation term in the analytical solution, assuming that heat supplied via support is homogeneously distributed over the whole volume of the droplet

Effect of support

International Journal of Heat and Mass Transfer 127 (2018) 92–106

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heating and evaporation of suspended water droplets: Experimental studies and modelling

P.A. Strizhak [a], R.S. Volkov [a], G. Castanet [b], F. Lemoine [b], O. Rybdylova [c], S.S. Sazhin [c,*]

[a] National Research Tomsk Polytechnic University, 30, Lenin Avenue, 634050 Tomsk, Russia
[b] Université de Lorraine, CNRS-UMR 7563, CS 25233, France
[c] Sir Harry Ricardo Laboratories, Advanced Engineering Centre, School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, UK

Effect of convection

The effect of droplet motion on Nu is taken into account but not its effect on the recirculation inside the droplet

Non-self-consistent model!

Effect of convection

Fuel 289 (2021) 119814

Contents lists available at ScienceDirect

Fuel

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

ELSEVIER

Full Length Article

Puffing/micro-explosion in rapeseed oil/water droplets: The effects of coal micro-particles in water

D.V. Antonov [a], P.A. Strizhak [a], R.M. Fedorenko [a], Z. Nissar [b], S.S. Sazhin [c,*]

Effect of thermal radiation

$$T = \frac{1}{R_d \xi}\left[\sum_{n=1}^{\infty} \Theta_n(t) v_n(\xi) + \frac{\mu_0 \xi}{1+h_0}\right],$$

where

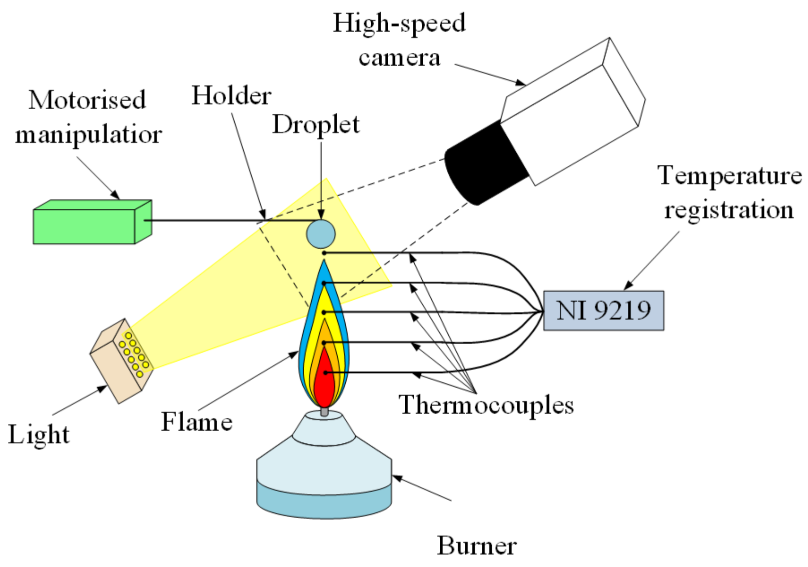
$$\Theta_n(t) = (q_n + f_n \mu_0)\exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right) + \frac{p_n}{\lambda_n^2}\left[1 - \exp\left(-\frac{\lambda_n^2 t}{R_d^2}\right)\right],$$

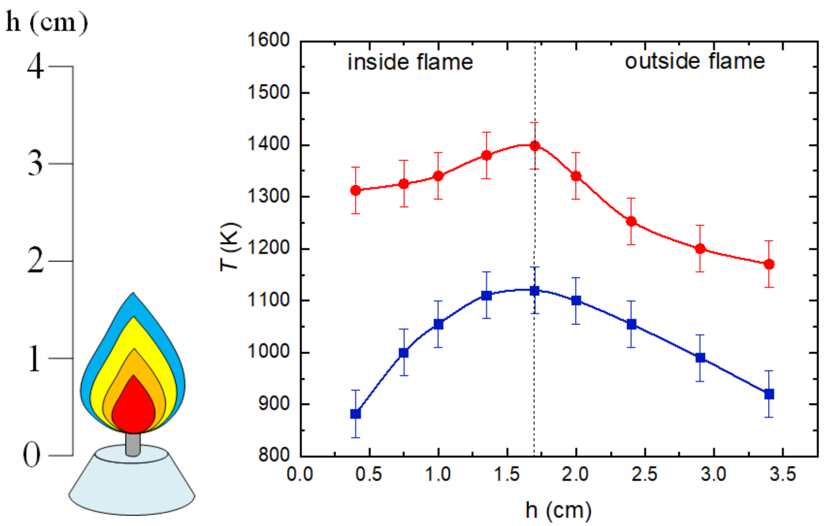
$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial R^2} + \frac{2}{R}\frac{\partial T}{\partial R}\right) + P(t, R)$$

$$P(R) \equiv P_r = 3\sigma \bar{Q}_a \theta_R^4 / (R_d c_l \rho_l)$$

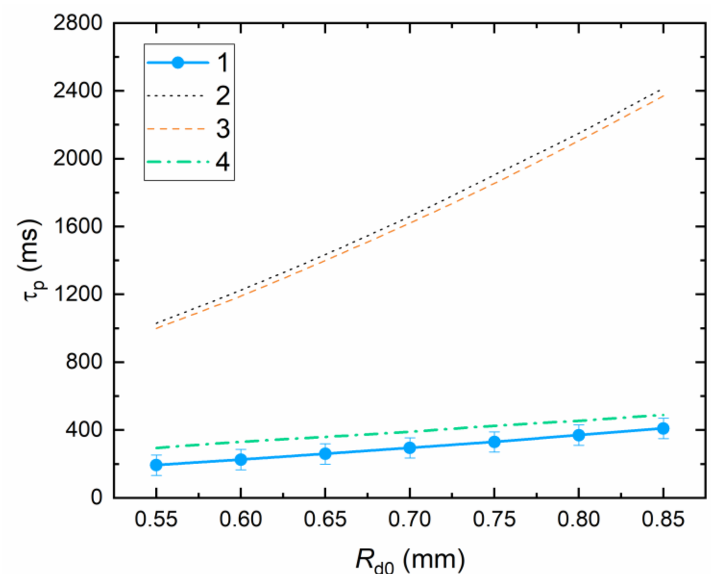
where θ_R is the radiative temperature (equal to gas temperature when gas is optically thick and external temperature when gas is optically thin); σ is the Stefan-Boltzmann constant; subscript $_l$ refers to liquid; Q_a is the efficiency factor of absorption (assumed equal to 1).

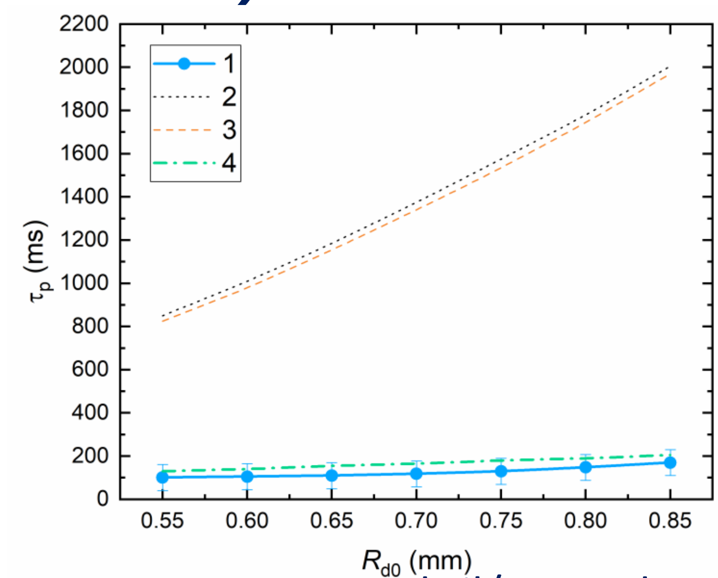
Effect of thermal radiation (experiment)





Effect of thermal radiation (results)





The times to puffing/micro-explosion of two-component rapeseed oil/water droplets introduced into the ethanol (a) and propane/butane mixture (b) flames versus droplet radii. The volume fractions of rapeseed oil and water were 90% and 10% respectively. In both cases droplets were located at h= 1.5 cm where ambient gas temperatures were 1,120 K and 1,400 K for ethanol and propane/butane mixture flames, respectively. Curves 1 show the experimental data; curves 2 show the predictions of the model when the effects of radiation and support were ignored; curves 3 show the predictions of the model when the effects of the support were taken into account, but the effects of radiation were ignored; curves 4 show the predictions of the model when the effects of radiation and support were taken into account.

Effect of thermal radiation

Combustion and Flame 233 (2021) 111599

Contents lists available at ScienceDirect

Combustion and Flame

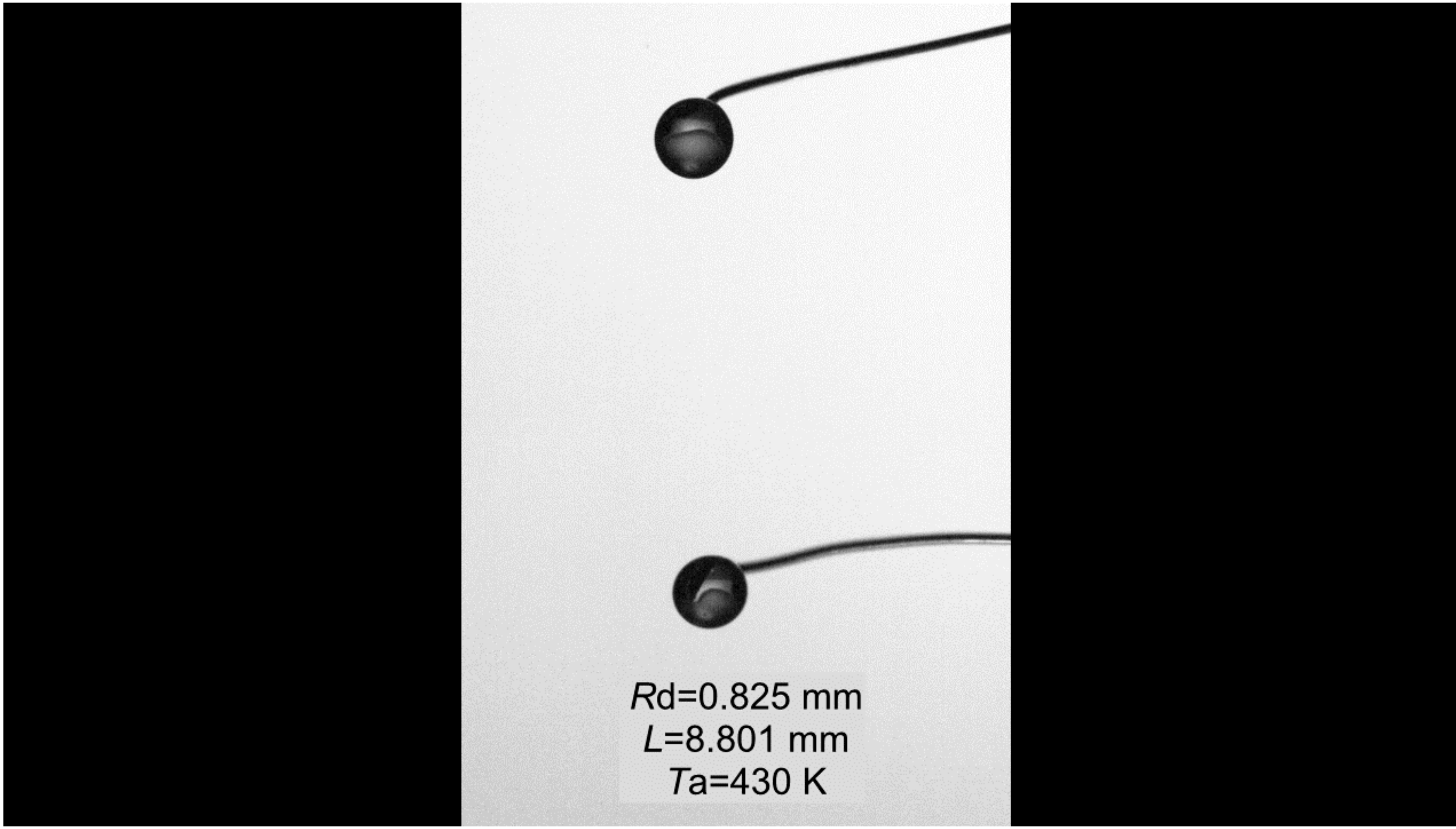
journal homepage: www.elsevier.com/locate/combustflame

Puffing/micro-explosion in composite fuel/water droplets heated in flames

D.V. Antonov [a], R.M. Fedorenko [a], P.A. Strizhak [a], Z. Nissar [b], S.S. Sazhin [c,*]

‘Grouping’ effects

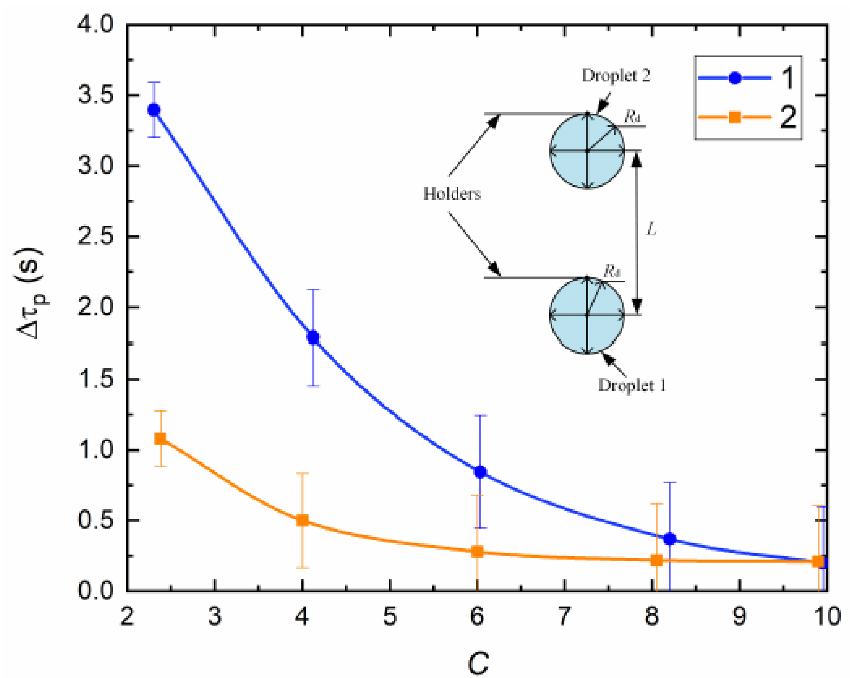
‘Grouping’ effects



‘Grouping’ effects

New correlations for Nu and Sh were obtained based on the numerical analysis of the flow and heat/mass transfer around two droplets in tandem. These correlation were used together with the previously described non-self-consistent model for puffing/micro-explosion

‘Grouping’ effects



The plots of the difference between times to puffing/micro-explosion for the downstream droplet (Droplet 2) (τ_{p2}) and the lead droplet (Droplet 1) (τ_{p1}), $\Delta\tau_p = \tau_{p2} - T_{p1}$, versus C=L/D for composite (1) and emulsion (2) droplets. Both composite and emulsion droplets contained rapeseed oil (with volume fraction 90%) and water (with volume fraction 10%). Ambient gas temperature and velocity were 430 K, and 0:1 m/s. Droplet radii and L were in the ranges 0.494 to 0.907 mm and 3.11 to 10.45 mm, respectively.

‘Grouping’ effects

International Journal of Heat and Mass Transfer 176 (2021) 121449

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

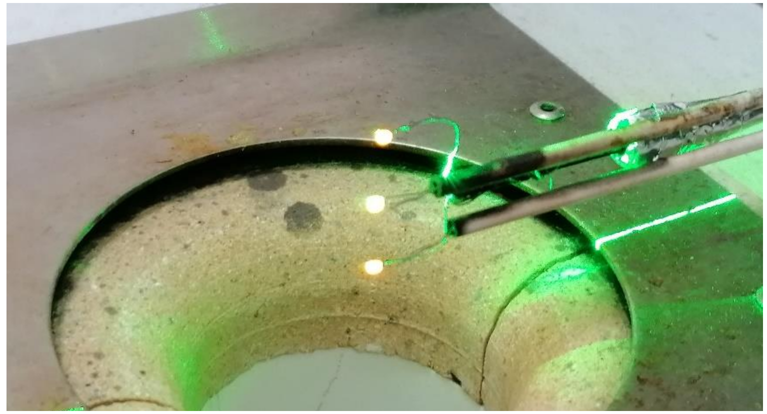
ELSEVIER

Puffing/micro-explosion of two closely spaced composite droplets in tandem: Experimental results and modelling

Check for updates

D.V. Antonov[a], R.M. Fedorenko[a], P.A. Strizhak[a], G. Castanet[b], S.S. Sazhin[c,*]

‘Grouping’ effects (3 droplets)



International Journal of Heat and Mass Transfer 181 (2021) 121837

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Temperature measurements in a string of three closely spaced droplets before the start of puffing/micro-explosion: Experimental results and modelling

D.V. Antonov[a], R.S. Volkov[a], R.M. Fedorenko[a], P.A. Strizhak[a], G. Castanet[b], S.S. Sazhin[c,d,*]

Effect of multi-component composite droplets

Liquid fuel mass diffusivity equation:

$$\frac{\partial Y_{\mathrm{li}}}{\partial t} = D_{\mathrm{l}}\left(\frac{\partial^2 Y_{\mathrm{li}}}{\partial R^2} + \frac{2}{R}\frac{\partial Y_{\mathrm{li}}}{\partial R}\right),$$

where $i \geq 1$, D_{l} is the liquid fuel mass diffusivity; this is assumed to be constant for all species.

The conditions at the outer and inner boundaries of the shell:

$$\alpha\left(\varepsilon_{\mathrm{i}} - Y_{\mathrm{lis}}\right) = -D_{\mathrm{l}}\left.\frac{\partial Y_{\mathrm{li}}}{\partial R}\right|_{R=R_{\mathrm{d}}-0}, \quad \left.\frac{\partial Y_{\mathrm{li}}}{\partial R}\right|_{R=R_{\mathrm{w}}+0} = 0,$$

where $Y_{\mathrm{lis}} = Y_{\mathrm{lis}}(t)$ are mass fractions of components i at the droplet's surface,

$$\alpha = \left|\dot{m}_{\mathrm{d}}\right| \cdot \left[4\pi\rho_{\mathrm{l}} R_{\mathrm{d}}^2\right]^{-1},$$

$\dot{m}_{\mathrm{d}}$ is the rate of droplet evaporation, and the initial condition:

$$Y_{\mathrm{li}}\left(R,t\right)\Big|_{t=0} = Y_{\mathrm{li0}}\left(R\right).$$

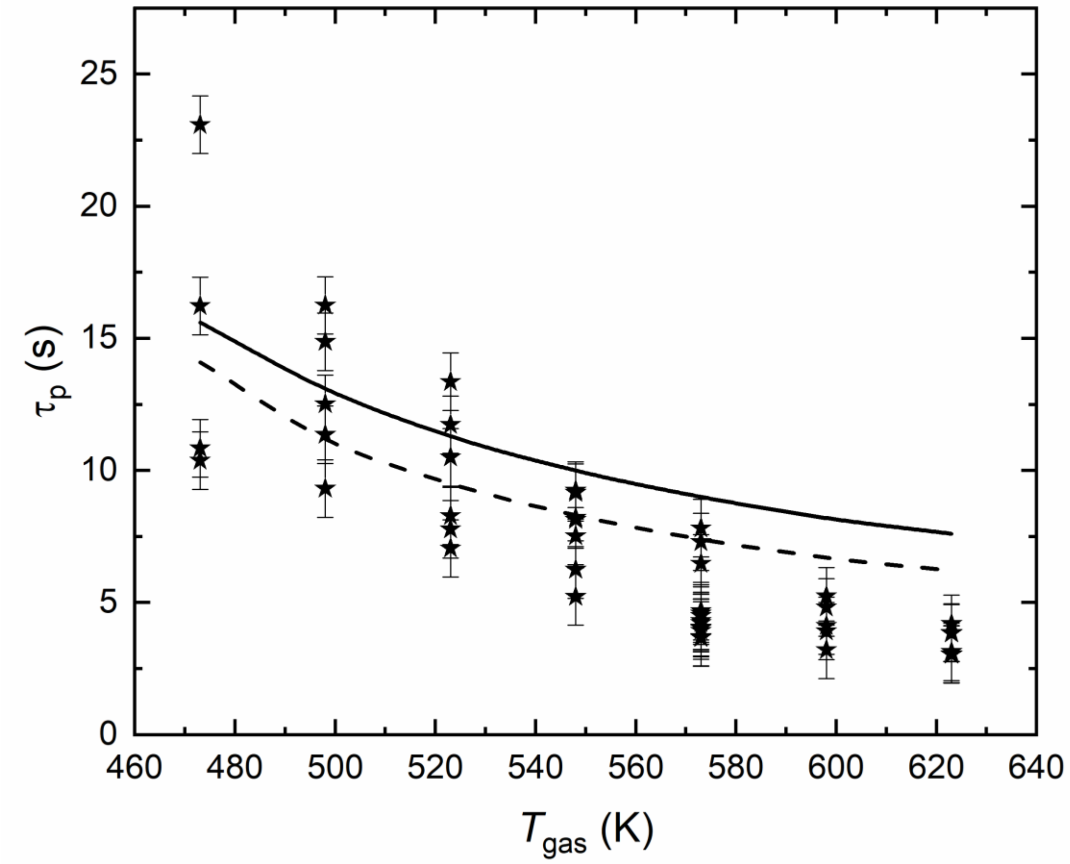
We assume that: $\varepsilon_{\mathrm{i}} = \frac{Y_{\mathrm{vis}}}{\sum_t Y_{\mathrm{vis}}},$

The analytical solution of liquid fuel mass diffusivity equation:

$$Y_{\mathrm{li}} = \varepsilon_{\mathrm{i}} + \frac{1}{R}\left\{\exp\left[D_{\mathrm{l}}\left(\frac{\lambda_0}{R_{\mathrm{d}}}\right)^2 t\right]\right\}\left[q_{\mathrm{i0}} - \varepsilon_{\mathrm{i}} Q_0\right]\upsilon_0 + \frac{1}{R}\sum_{n=1}^{\infty}\left\{\exp\left[-D_{\mathrm{l}}\left(\frac{\lambda_{\mathrm{n}}}{R_{\mathrm{d}}}\right)^2 t\right]\right\}\left[q_{\mathrm{in}} - \varepsilon_{\mathrm{i}} Q_{\mathrm{n}}\right]\upsilon_{\mathrm{n}}.$$

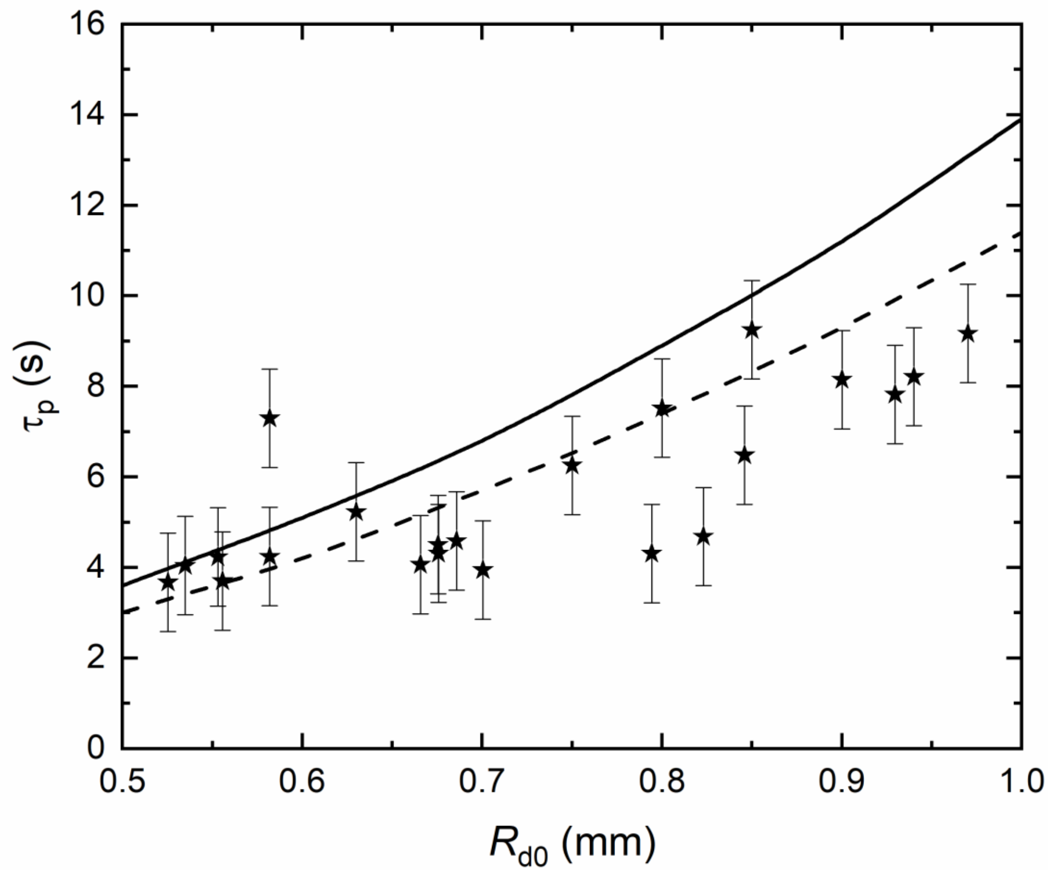
S.S. Sazhin, E. Shchepakina, V.A. Sobolev, D.V. Antonov, P.A. Strizhak, Puffing/micro-explosion in composite multi-component droplets, *International Journal of Heat and Mass Transfer*. 2021. (almost accepted)

Experimental versus modelling results



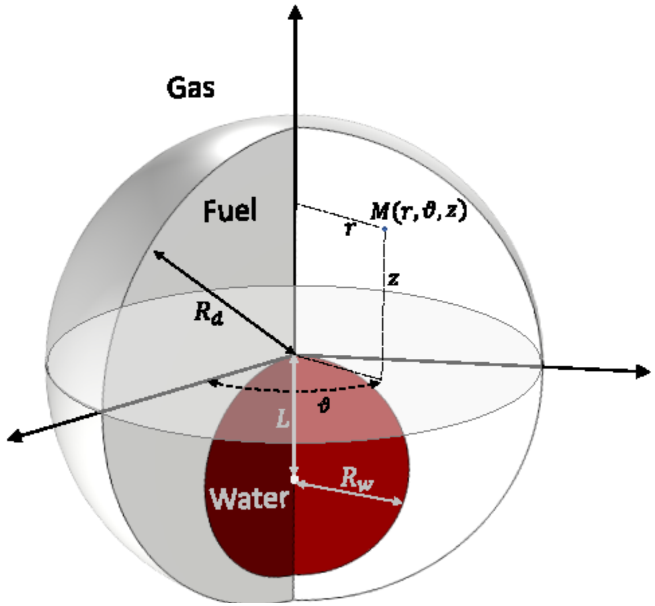
Times to puffing/micro-explosion of water/kerosene droplets versus gas temperatures, observed experimentally (stars) and predicted by the model assuming that puffing/micro-explosion starts when the temperature at the water/kerosene interface becomes equal to the water nucleation temperature ($T_W = T_N$) (curves). The solid curve shows the case when the contributions of all kerosene components were considered; the dashed curve shows the case when kerosene was approximated by n-decane.

Experimental versus modelling results



Times to puffing/micro-explosion of water/kerosene droplets versus initial droplet radii, observed experimentally (stars) and predicted by the model assuming that puffing/micro-explosion starts when the temperature at the water/kerosene interface becomes equal to the water nucleation temperature ($T_W = T_N$) (curves). The solid curve shows the case when the contributions of all kerosene components were considered; the dashed curve shows the case when kerosene was approximated by n-decane.

Effect of the water sub-droplet shift



Effects of water subdroplet shift on the start of puffing/micro-explosion in composite fuel-water droplets

G. Castanet[1], D.V. Antonov[2], P.A. Strizhak[2], S.S. Sazhin[3]*

[1] Université de Lorraine, CNRS-UMR7563, CS 25233, France

[2] National Research Tomsk Polytechnic University, 30, Lenin Avenue, 634050, Tomsk, Russia

[3] Advanced Engineering Centre, School of Architecture, Technology and Engineering, University of Brighton, Brighton, BN2 4GJ, UK

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Thank you for your attention

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SoC 2021

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