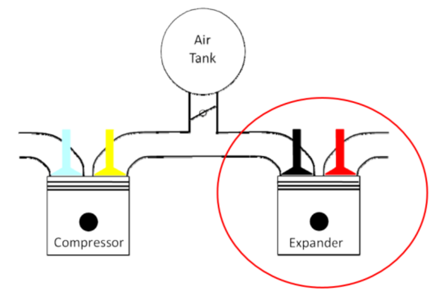
Heating and evaporation for semi-transparent droplets in gasoline sprays: a parametric study

R. Regi and E Sazhina

Sir Harry Ricardo Laboratories (SHRL) at Advanced Engineering Centre (AEC), School of CEM
University of Brighton

Introduction: Heating fuel droplets by thermal radiation of in-cylinder flame is relevant under novel concepts for gasoline engines:
a) split-cycle engine b) gasoline direct injection engine.
The concept of split-cycle engine with compressor and expander is illustrated by a schematic diagram:



Methodology: The numerical simulation tools are:

1. **ANSYS FLUENT** Computational fluid dynamics (CFD) software. Simulations for blackbody opaque droplets under infinite thermal conductivity (ITC) model.
2. **SHRL_BB code** for multicomponent gasoline (20 components) blackbody opaque droplets.

Transient heat conduction equation for distribution of temperature inside droplet under effective thermal conductivity (ETC) model. :

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

where thermal diffusivity $\kappa = \frac{\kappa_{eff}}{c_l \rho_l}$ is described by Eqns 3.72 of [1]).
Boundary conditions are based on convective heat flux from gas at temperature *Tg*.
Replacing *Tg* by *Teff* accounts for evaporation:

$$T_{eff} = T_g + \frac{\rho_l L \dot{R}_{dE}}{h} \qquad \text{Eqn 4.30 of [1].}$$

Further extension for a blackbody droplet reads: $T_{eff} = T_g + \frac{\rho_l L \dot{R}_{dE}}{h} + \frac{\sigma T_{rad}^4}{h}$

3. **SHRL_ST code:** This is SHRL in-house code for semi-transparent fuel droplets with the ETC model. Temperature of liquid inside the droplet for semi-transparent droplets is governed by

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

where $P(R)$ describes heating by thermal radiation. It is approximated by

$$P(R) = 3a\sigma R_d^{b-1}\,\theta_R^4 / cb\rho_b \qquad \text{(Eqn 3.94 of [1])}$$

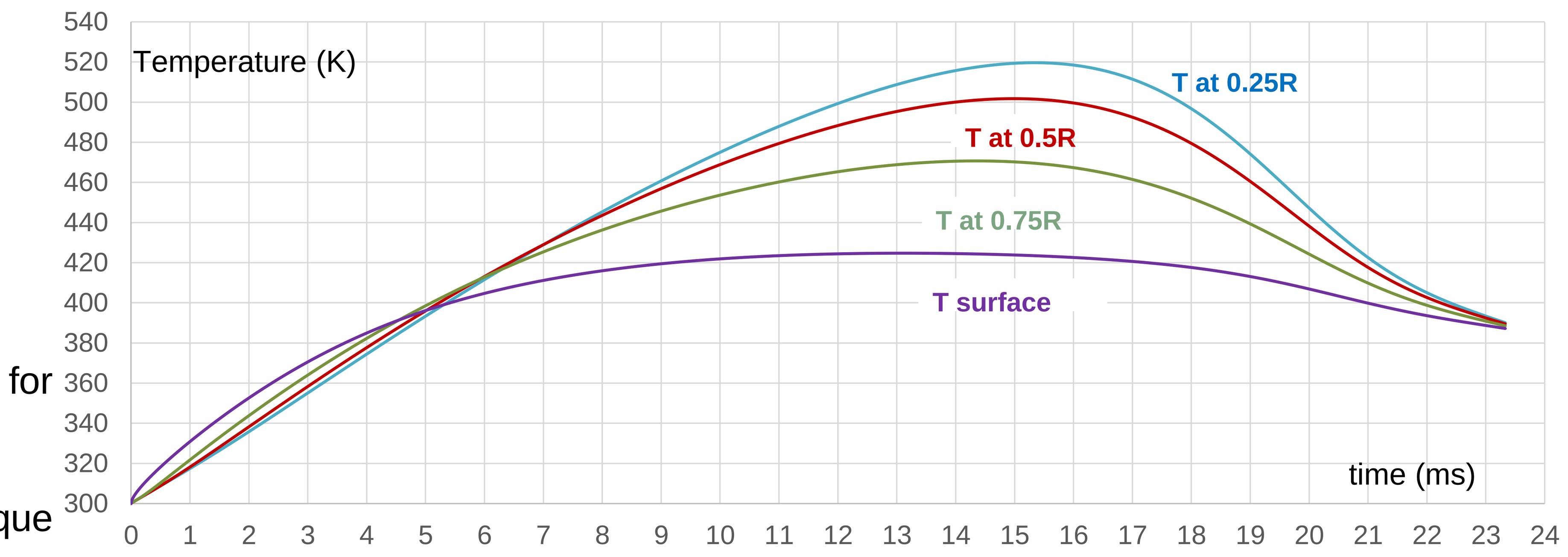
with empirical parameters a and b depending on external radiation temperature

Reference: [1] Sazhin, S.S. (2014) *Droplets and Sprays*, Springer-Verlag

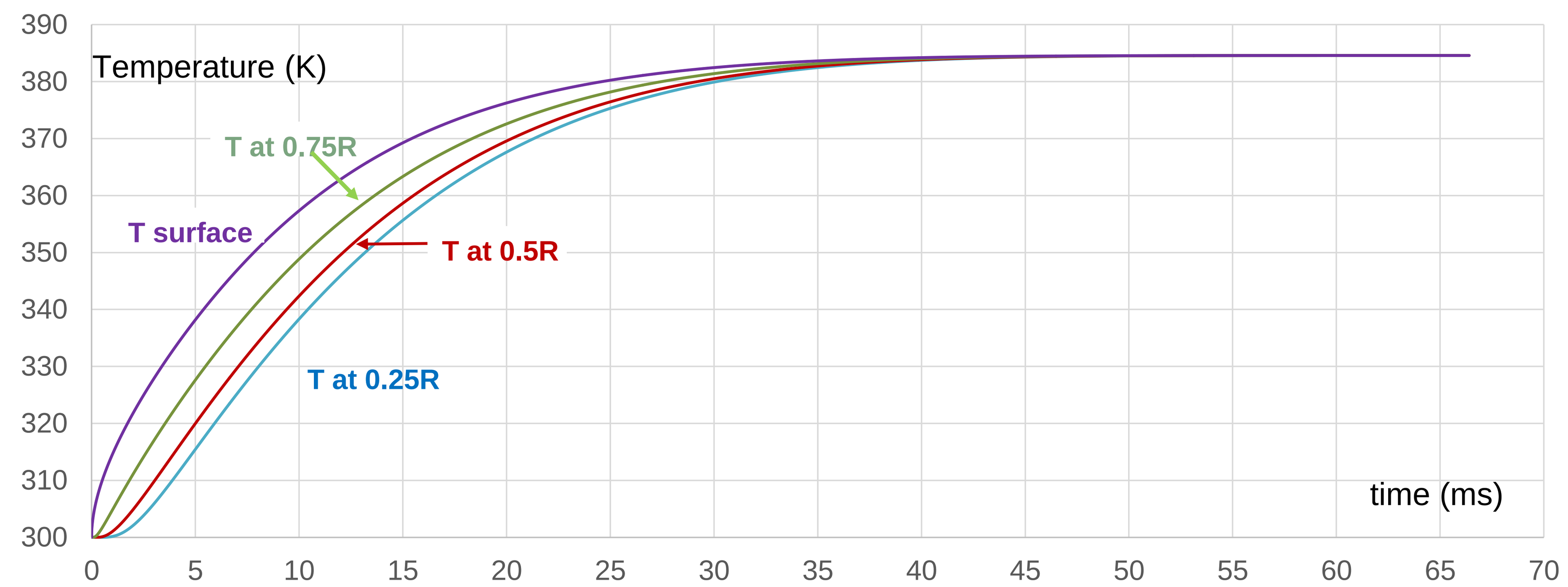
Operating parameters for numerical simulations:

- Droplets of initial radii 6 µm, 12 µm and 45 µm
- Fuel temperature in the range 280 K – 360 K
- Radiation temperature of 1000 K – 2200 K
- Gas temperature in the range 400 K – 800 K
- Droplet velocity varies from zero to 141 m/s
- Pressure is in the range of 0.1MPa – 0.9 MPa.

Overshoot of temperature over asymptotic value is observed for semi-transparent (ST) droplets

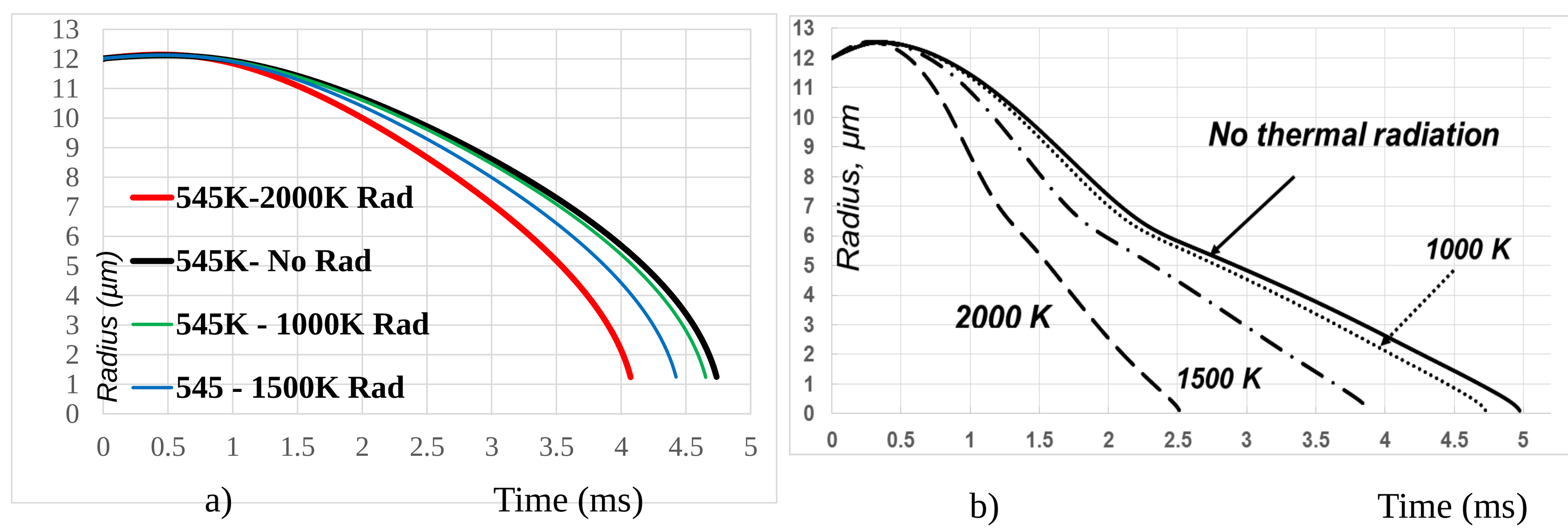


Heating and evaporation of n-heptane semi-transparent droplet under ETC model in the presence of thermal radiation from a flame. Thermal radiation temperature is 2200 K.
Droplet diameter is 90 µm, gas T = 545 K, gas pressure 0.9 MPa, stationary droplet with initial T = 300 K..



Heating and evaporation of n-heptane droplet under ETC model in the absence of thermal radiation
Droplet diameter is 90 µm, gas T = 545 K, gas pressure 0.9 MPa, stationary droplet with initial T = 300 K.

Semi-transparent n-heptane droplet *vs* multicomponent gasoline blackbody droplet.



a) Radius (µm) as function of time (ms) by SHRL_ST code for n-heptane semi-transparent droplet
b) Radius (µm) *vs* time (ms) for multicomponent gasoline blackbody droplet.
In both cases, a) and b), droplet initial radius is 12 µm, gas T = 545K and pressure is 0.9MPa. The ETC model is taken for both cases. Values of thermal radiation temperatures are shown near the curves.

Summary of influence of thermal radiation at 2000 K on evaporation time (ms)

T radiation (K)	No Radiation	2000K	% decrease
Droplet diameter (µm)	CFD ANSYS FLUENT		
12	0.336	0.285	15%
24	1.170	0.860	26%
90	12.267	5.040	59%

ANSYS FLUENT CFD: Fuel T = 300 K, gas T = 545 K, pressure = 0.1 MPa.

T radiation (K)	No Radiation	2000K	% decrease
Droplet diameter (µm)	SHRL Semi-Transparent (ST) droplets		
12	0.951	0.915	4%
24	3.804	3.390	11%
90	53.499	26.222	51%

SHRL_ST code: Fuel T = 300 K, gas T = 545 K, pressure = 0.1 MPa.

	SHRL _ST	SHRL _BB
No Radiation	4.737	5
T_rad = 2000 K	4.073	2.5
% decrease	14%	50%

Comparison of evaporation times (ms) by the SHRL_BB and SHRL_ST codes. Droplet radius 12 µm, gas T = 545K and pressure = 0.9MPa. There is a decrease of 14% in evaporation time for the ST droplet. For the BB droplet, it makes 50%.

Conclusions:

Three numerical modelling tools: ANSYS FLUENT CFD, SHRL_ST and SHRL_BB were used for simulations. The results show that

- Decrease in evaporation times is more significant for larger droplets than for smaller fuel droplets
- Blackbody approximation gives larger reduction of evaporation time for a given radiation temperature when compared with semi-transparent approximation, as it can be expected.
- Maximal droplet temperature shows a significant overshoot over asymptotic wet-bulb temperature for the semi-transparent model. This is even more pronounced in inner layers. This overshoot is not observed for opaque droplets (ANSYS CFD and SHRL_BB). This qualitative change in heating profile for ST model is important for better understanding of micro-explosion phenomena in droplets

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