Simple model for the extinguishing performance of foams in pool fires

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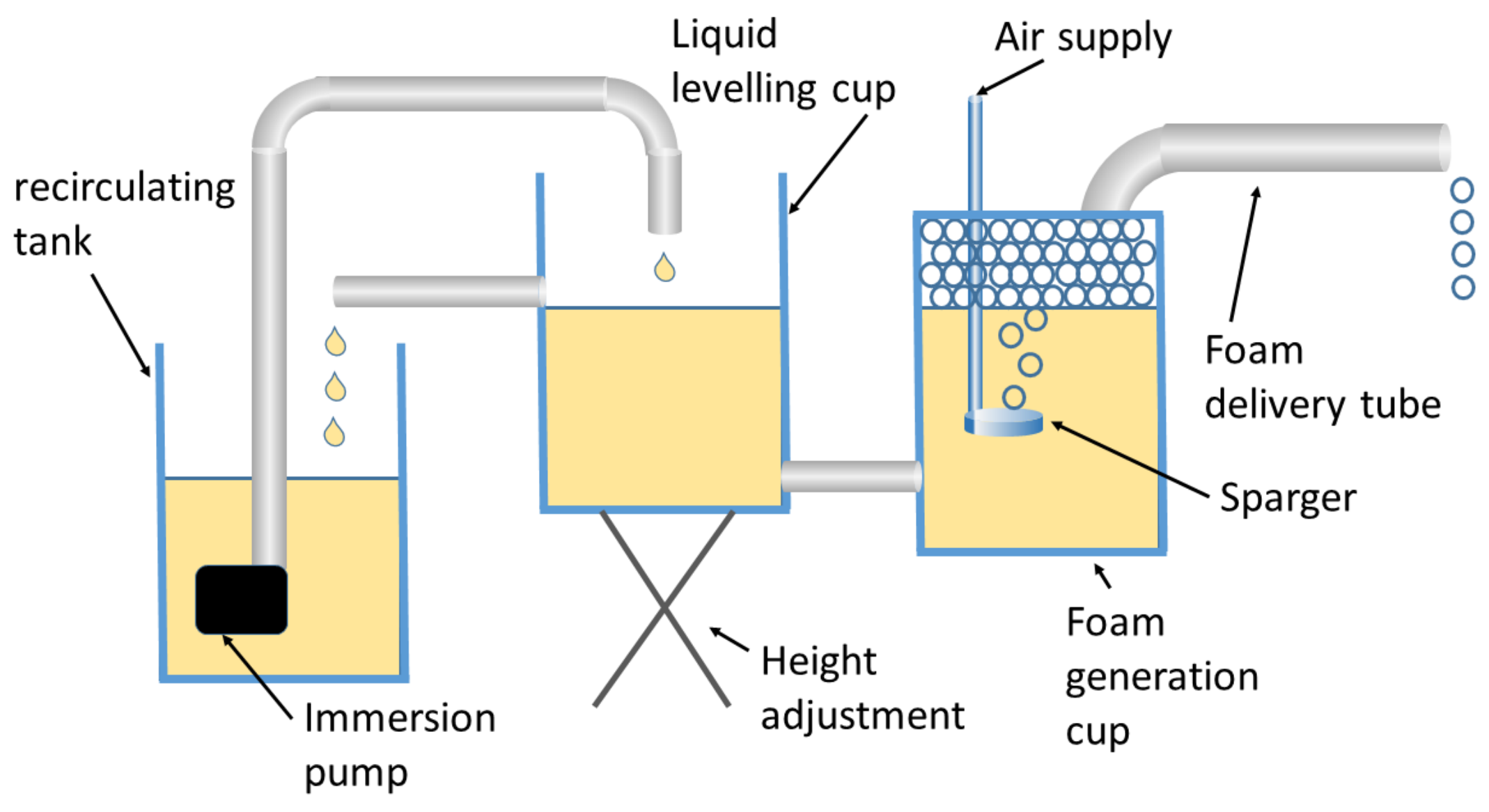
Bench scale fire extinguishing test

Foams are a very effective and widely used method to extinguishing fires. They are especially useful to extinguish large pool fires of liquid fuels. To test the capabilities of newly developed foams and foam components, a bench scale fire extinguishing test has been developed at NRL. The sophisticated design of the foam generator guarantees highly similar foam properties at different foam flow rates [3].
Extinction time data of > 200 extinguishing tests with > 80 different foam solutions at many different foam flow rates has been generated at NRL with the bench scale test.
The goal is to find a simple mathematical model which correlates material data of the foam solution to experimental results to further cut back the number of fire tests necessary for the development of a new foam.

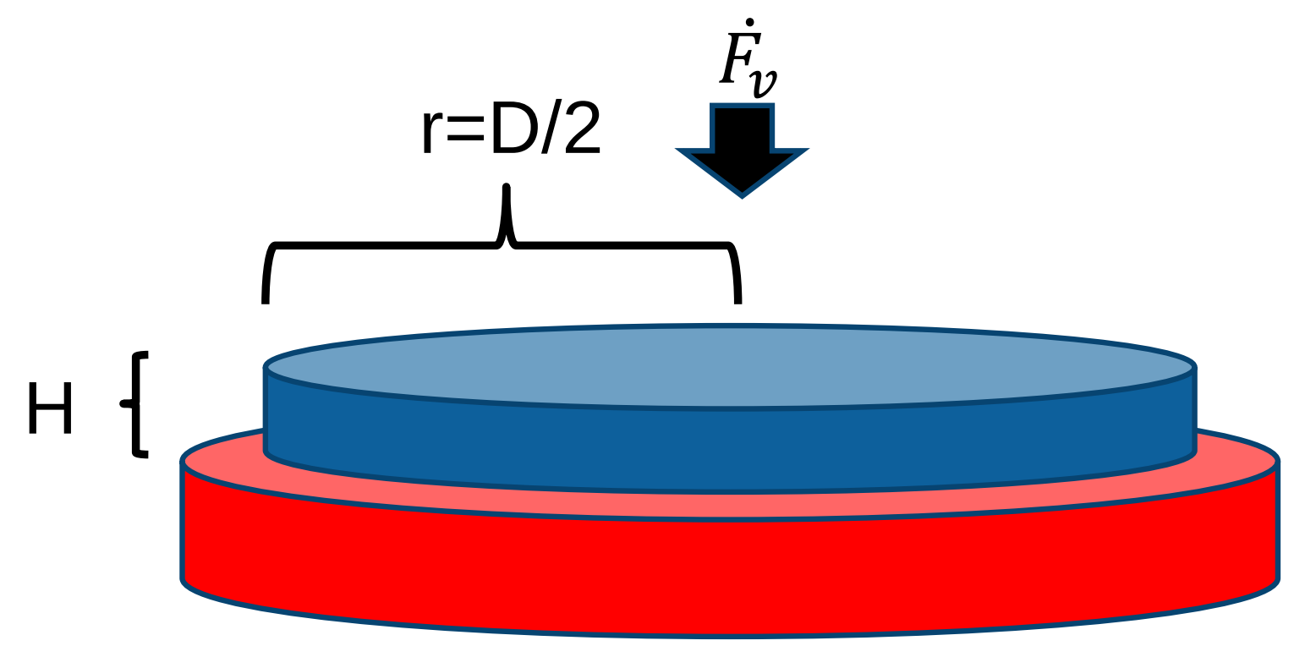


Foam generator for bench scale test

RefAFFF bench scale fire test on heptane pool

502W Formulation fire test on heptane pool

Mathematical model for the bench scale fire extinguishing test



$$\boxed{\rho \pi H_f D \frac{dD}{dt} = \rho F_v - \rho \frac{\pi}{4} D^2 R_{dfu} - \rho \pi H_f D R_{dfi}}$$

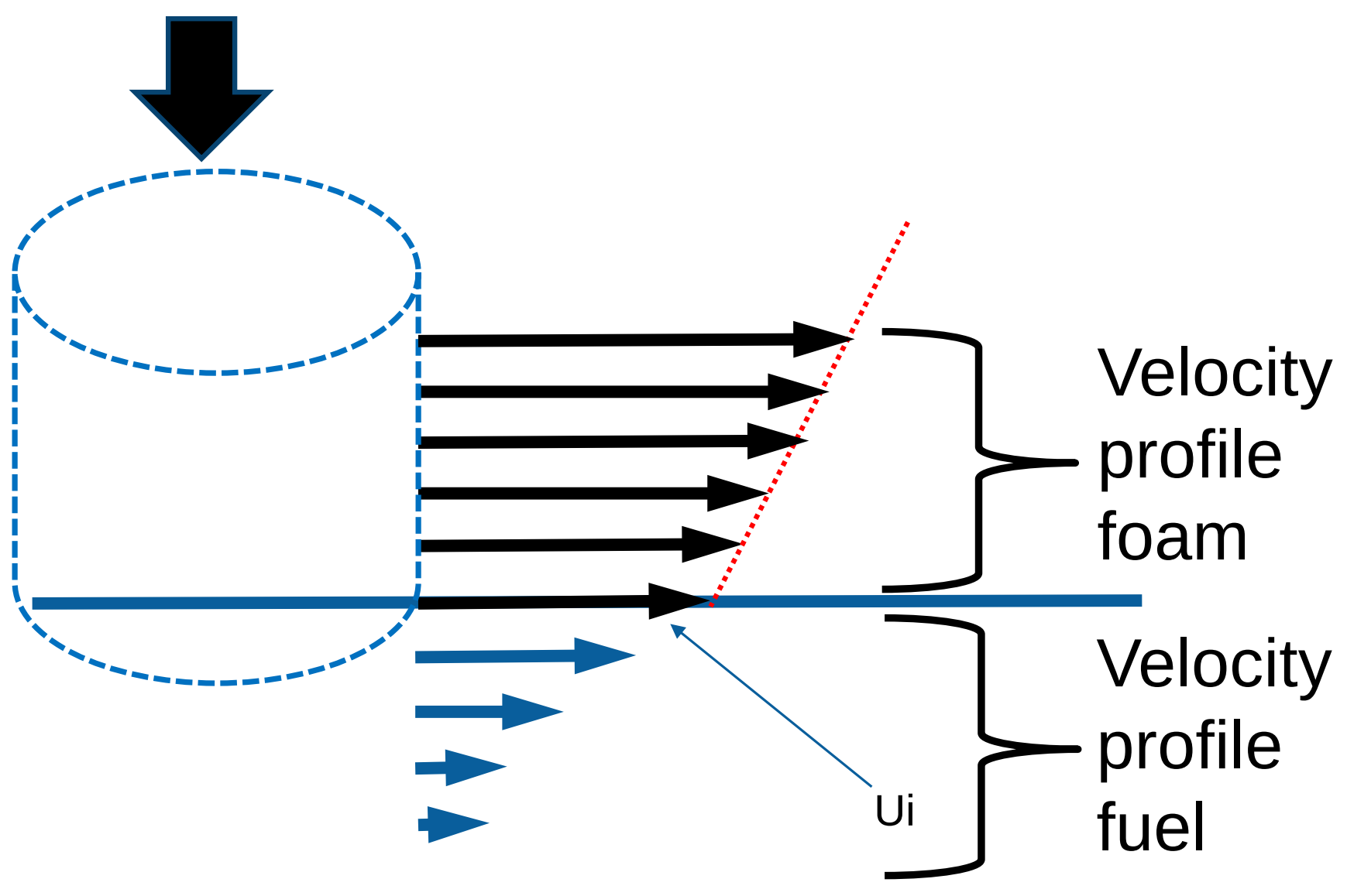
Model assumptions

- Constant height Hf of cylindrical foam layer with variable diameter D
- Uniform density of foam
- No drainage
- Constant mass loss Rdfu due to fuel/ foam interaction proportional to area covered by foam
- Mass loss due to fire/ foam interaction at constant rate Rdfi proportional to circumference of foam layer
- Foam is applied in the center of the circular pan with constant rate Fv
- Fire is extinguished when diameter of foam is equal or larger that diameter of the cylindrical pool

Couette Flow Assumption

One additional assumption is that the velocity of the foam at the fuel/foam interface Ui is a constant at a given radius Rt around the foam input location. It changes with height at a constant rate
By integrating over the velocity profile and solving for Hf the height of the foam on top of the pool can be determined:

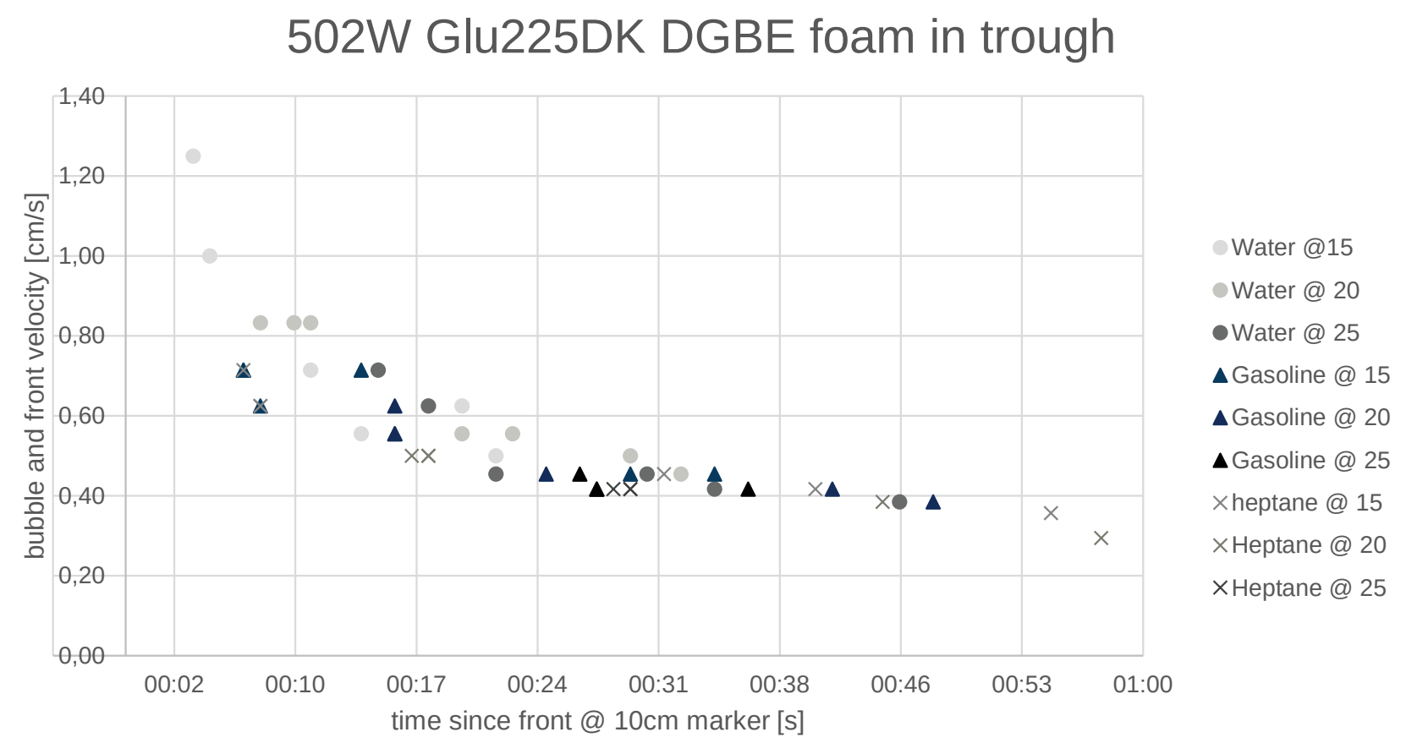
$$\boxed{F_v = \int_0^{H_f} 2\pi r\, u(h) dh \rightarrow H_f = -\frac{\mu\, u_i}{\tau} + \sqrt{\frac{\mu^2 u_i^2}{\tau^2} + \frac{\mu F_v}{2\pi R_t \tau}}}$$

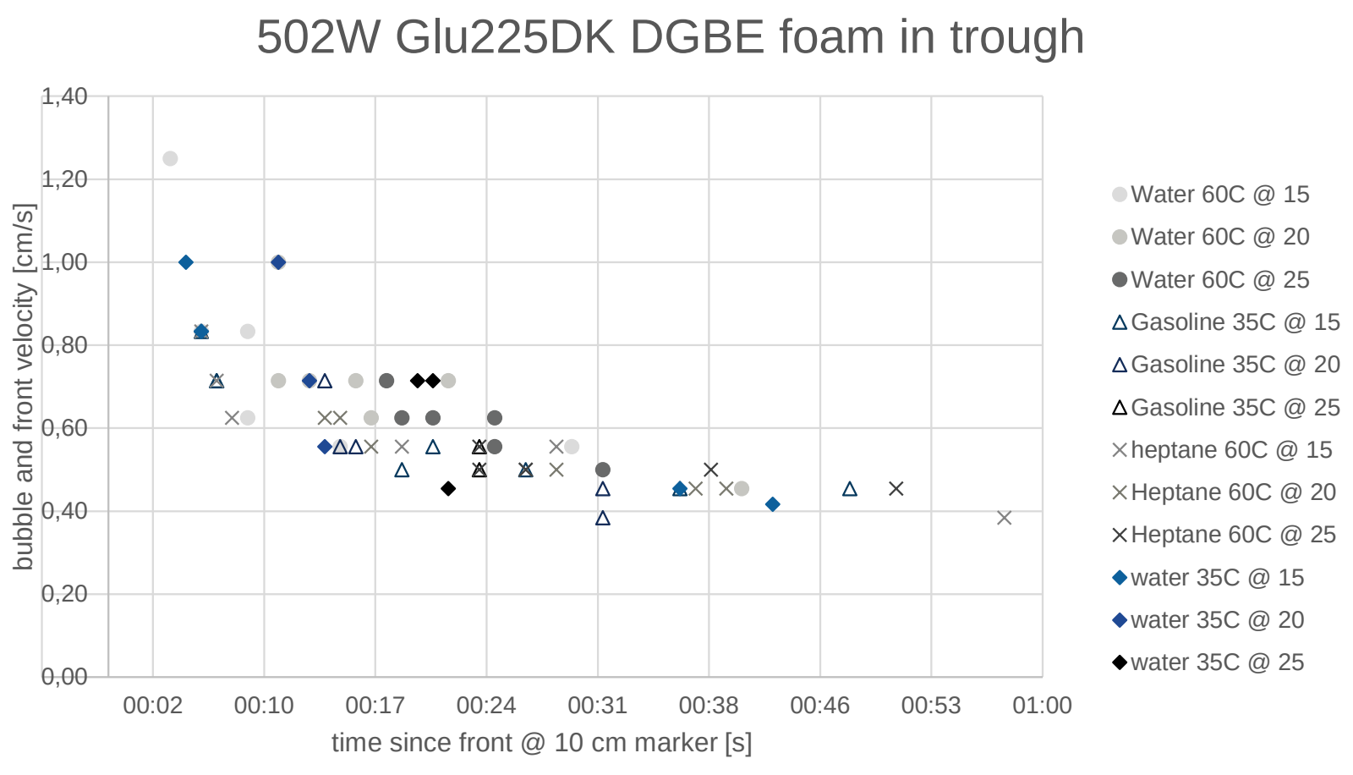


Validation in 1D Trough

In a one dimensional trough, if the top layer is the fastest layer, the tip of the foam should have the same velocity as all other points at the top of the foam. In the other case, the tip of the foam should move faster than other points on the top of the foam, with the difference increasing with the distance from the tip of the foam. The same holds for the time domain.

To measure the speed of different points at the top layer of the foam, the movement of bubbles at the top of the foam has been observed. The times when the bubbles passed the 10 cm mark, 15 cm mark etc up to the 35 cm mark have been recorded, when applicable. To compute the velocity of the foam bubbles, the travel time between two marks has been divided by the distance (5 cm). The resulting velocity in dependence of the time of the passing of the first marker has been plotted.





*The work presented here was done during a stay at NRL as part of the ESEP exchange program.

Fitting model to experimental data

Model predicts extinguishing times tex at given foam flow rates Fv using a set of parameters (Rdfi, Rdfu etc) named P:

$$t_{model\ i\ j} = Model(F_{v\ i\ j}, P_{k\ j})$$

For the foam solution j, different foam flow rates i and the set of parameters P

To fit the model to the experimental data, the sum of squares has to be minimized. This is done by adjusting the parameters P:

$$\textstyle\sum_i \left(t_{ex\ ij} - t_{model\ ij}\right)^2$$

$$\textstyle\sum_i \left(t_{ex\ ij} - Model(F_{v\ i\ j}, P_{k\ j})\right)^2$$

For one foam solution j

Initial guesses for the set of parameters P could be found by investigating limit cases:

$$R_{dfu\ initial\ guess} = \frac{4F_v}{\pi D_{pool}^2}.$$

With the highest foam flow rate Fv without successful extinguishment

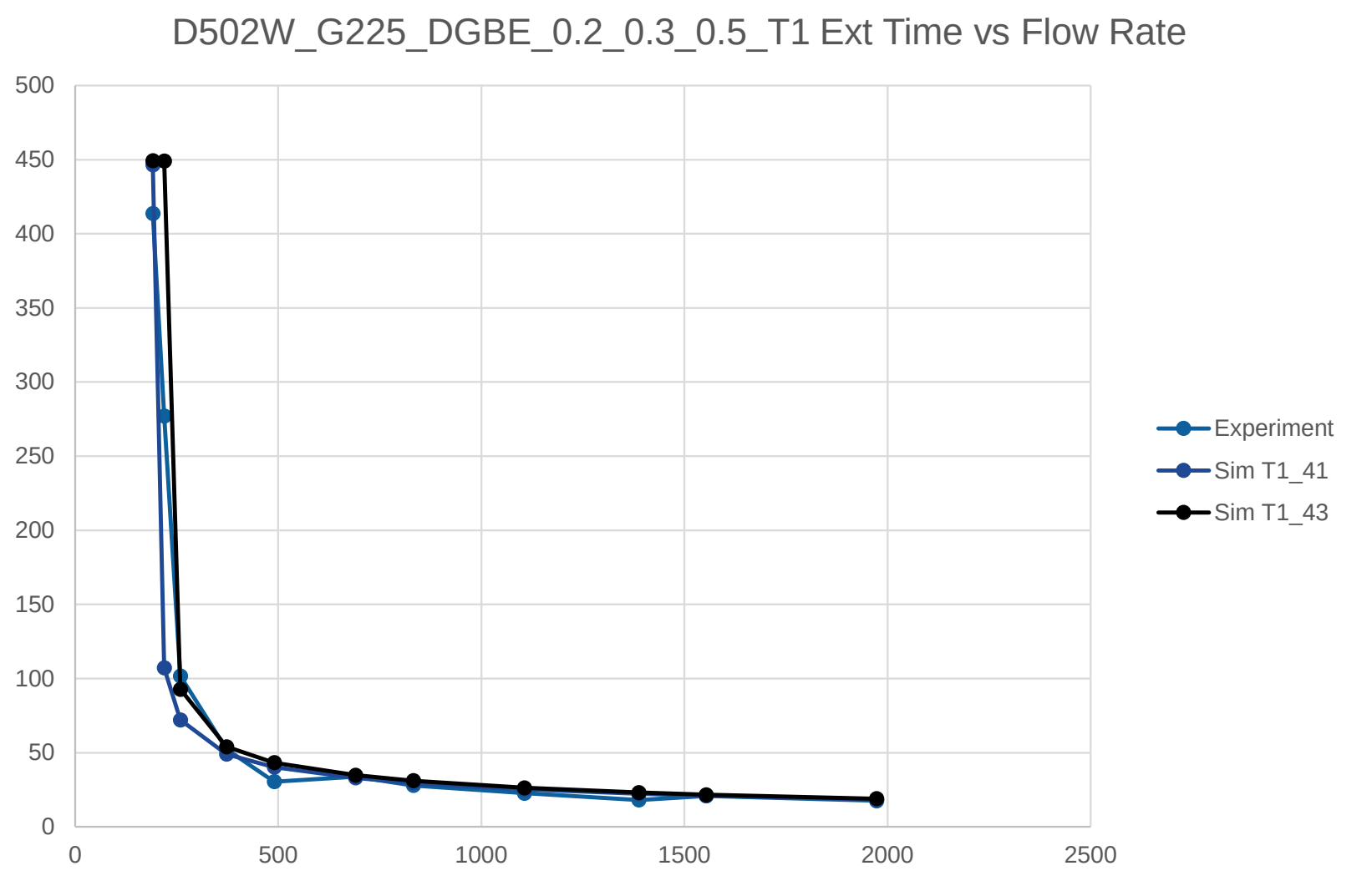
$$u_{i\ plug\ initial\ guess} = \frac{\left(D_{pool}^2 - 0.01^2 m^2\right)}{16 R_t t_{ex\ plug}}$$

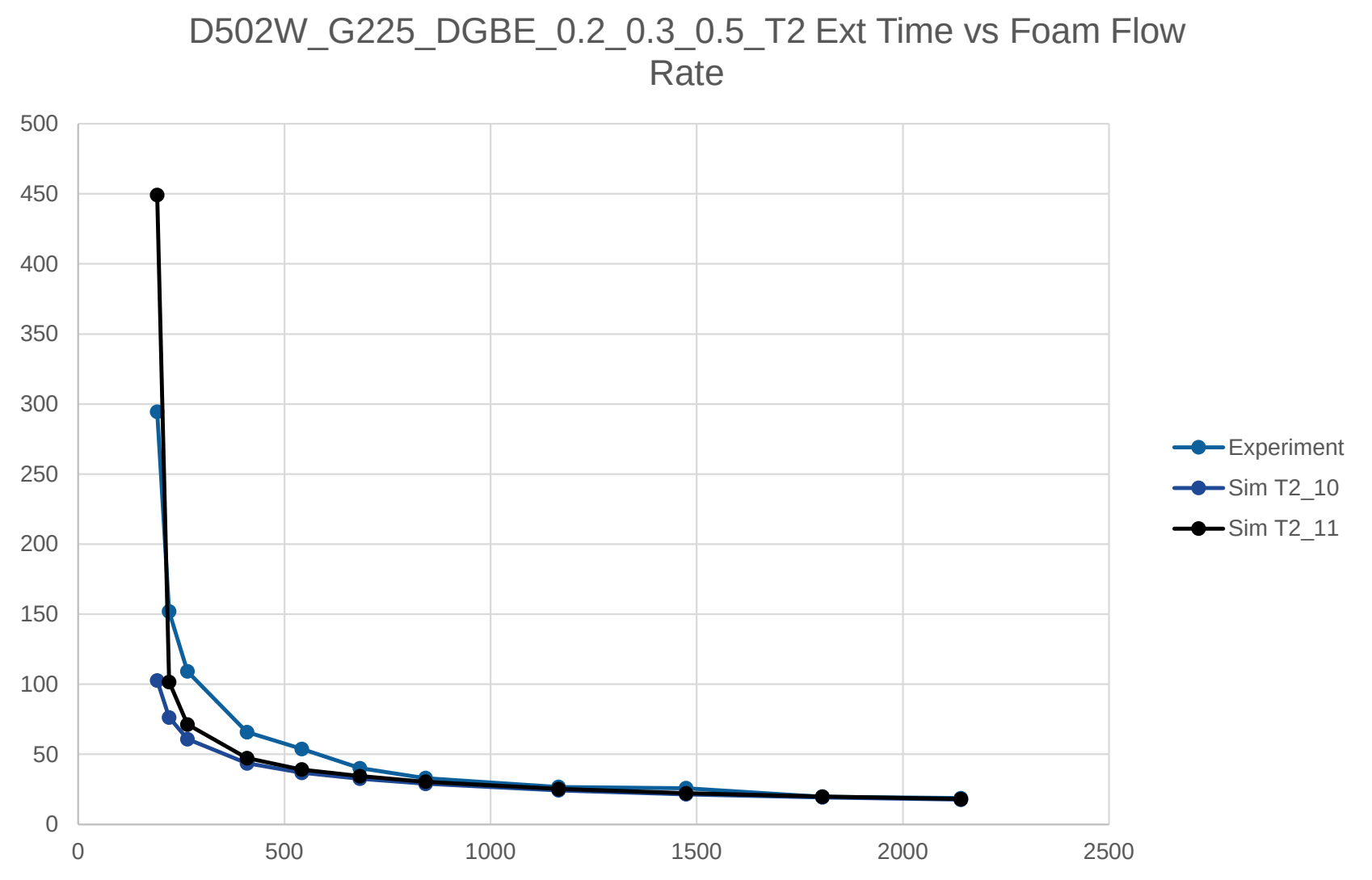
With the extinguishing time tex at the highest foam flow rate

$$R_{dfi\ initial\ guess} = \frac{F_v - \frac{\pi}{4} D_{pool}^2 R_{dfu}}{\pi H_f D_{pool}}$$

With the median foam flow rate Fv

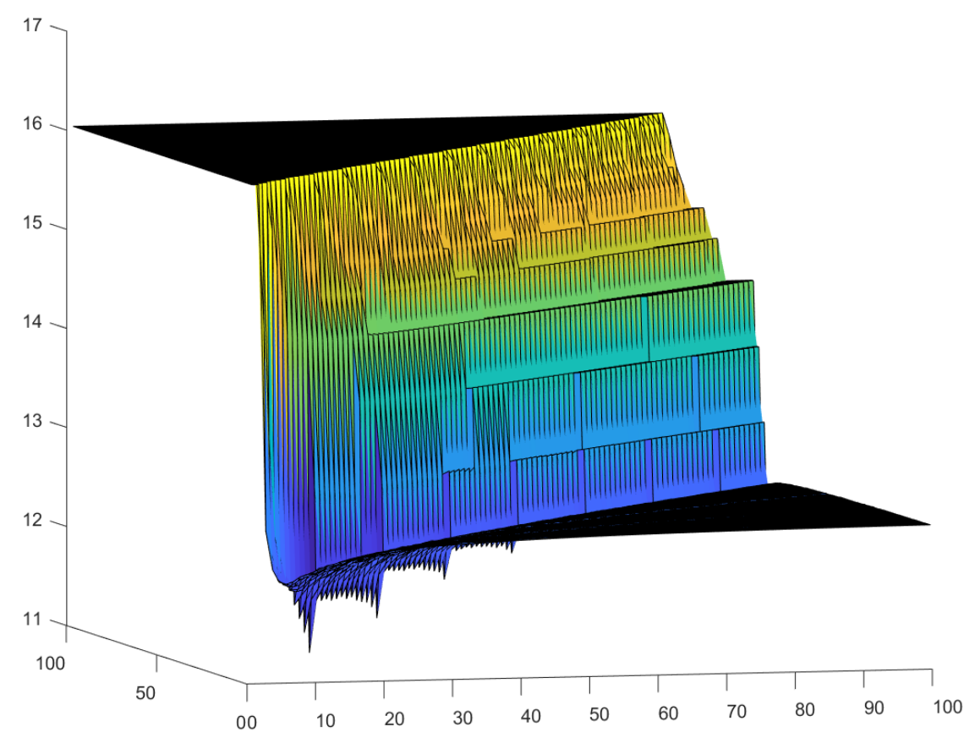
Depending on the set of data chosen, the quality of the fit of the model to the experimental data varies.

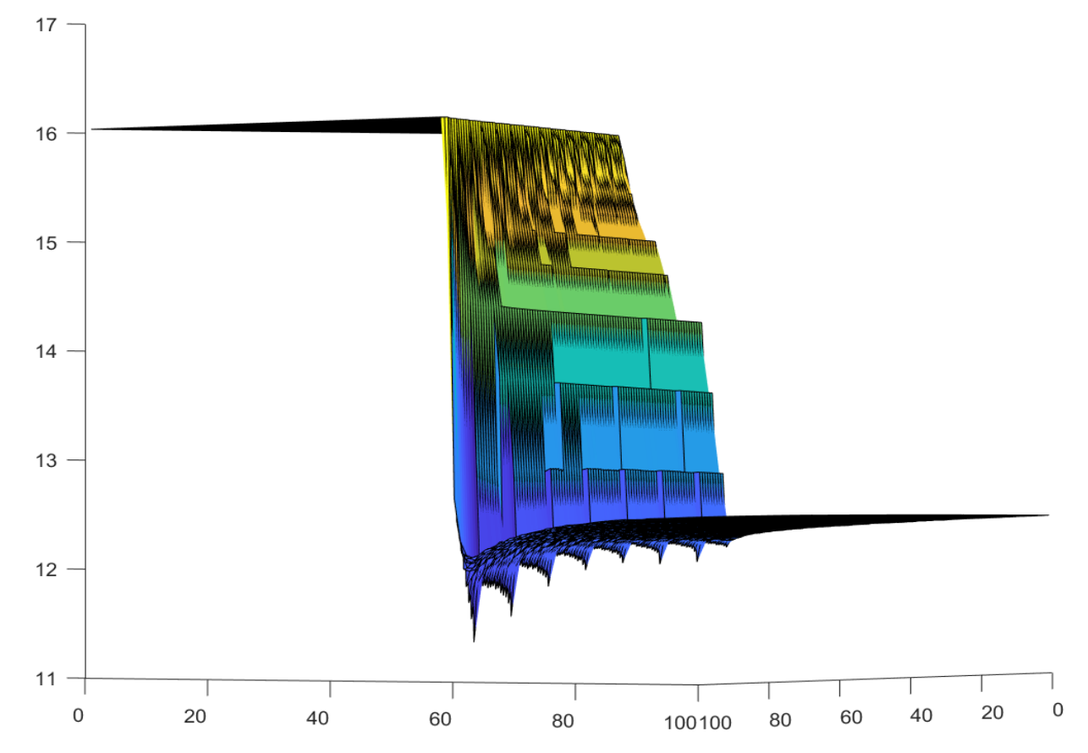




Numerical Challenges:

The residual for a set of parameters with R_{dfu} = 2.333 * 10^-5 m/s, R_{dfi} = 0 … 5*1.8 * 10^-3 m/s, U_i = 0 … 5*0.02 m/s for the model to 0.2% D502W 0.3% G225 0.5% DGBE_T1 foam on heptane has been plotted, with ln(residual) as the Z-axis and values proportional to R_{dfi} and U_i on the X and Y axis. The resulting figures below show that the minimum of the residual is extremely difficult to find, because it is 'hidden' in a narrow valley with many local minima which confuse the minimum seeking algorithm. High numerical effort is necessary to identify the minimum provided by a sophisticated algorithm, e.g. MatLab patternsearch.





Results

Correlation Rdfu to Degradation time

	5-26	6-7a	6-7b
All (63)	-0.36	-0.43	-0.41
CapStone (9)	-0.12	-0.26	0.05
502W (22)	-0.61	-0.55	-0.51

Correlation Ui to Cover time

	5-26	6-7a	6-7b
All (63)	-0.03	-0.03	-0.03
CapStone (9)	-0.78	-0.79	-0.69
502W (22)	-0.22	-0.13	-0.17

$$\frac{\sum_i \left(a_i - \bar{a}\right)\left(b_i - \bar{b}\right)}{\sqrt{\sum_i \left(a_i - \bar{a}\right)^2 \sum_i \left(b_i - \bar{b}\right)^2}}$$

Pearson correlation coefficient (PCC)

Presented are the results of three model runs. Because at 'no extinguishing' there is no associated extinguishment time, it is approximated by a very high extinguishing time. 999s in simulation 5-26 and 9999s in simulations 6-7a and 6-7b. To improve the stability of the model, in cases where for one mixture there was extinguishment in all fire tests, additional data was introduced with no extinguishment at flow rate close to zero (6-7a) and half of the lowest tested foam flow rate (6-7b). In all three cases the correlation between destruction by fuel predicted by model (Rdfu) and foam degradation time is far better for the 502W subset. Similar, for the CapStone (an AFFF) subset the correlation between the velocity of the foam at the foam/fuel interface predicted by the model (Ui) and experimental cover time is far better than the other correlations.

This correlation is remarkable, because only very simple assumptions about foam spread, foam destruction by the fuel and destruction by fire at the rim of the foam disc are made. Radiation to the top surface of the foam is ignored.

References

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3. Ramagopal Ananth, Arthur W. Snow, Katherine M. Hinnant, Spencer L. Giles, John P. Farley, Synergisms between siloxane-polyoxyethylene and alkyl polyglycoside surfactants in foam stability and pool fire extinction, Colloids and Surfaces A 579 (2019) 123686

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