caspus engineering
analysis | simulation | design

RADIATION ATTENUATION THROUGH WATER SPRAYS

Dr Andrei Horvat

Caspus Engineering
Didcot, December 2020

Content

- Introduction
- System layout and operating parameters
- Spray behaviour
- Thermal radiation
- Single and double water spray curtain
- Parametric analysis
- Operating parameters of the improved system
- Conclusions and recommendations

Introduction

Accident scenario of a fuel tank fire

- nearest building located 45 m from the fire
- thermal irradiation loading of 6 kW/m^2

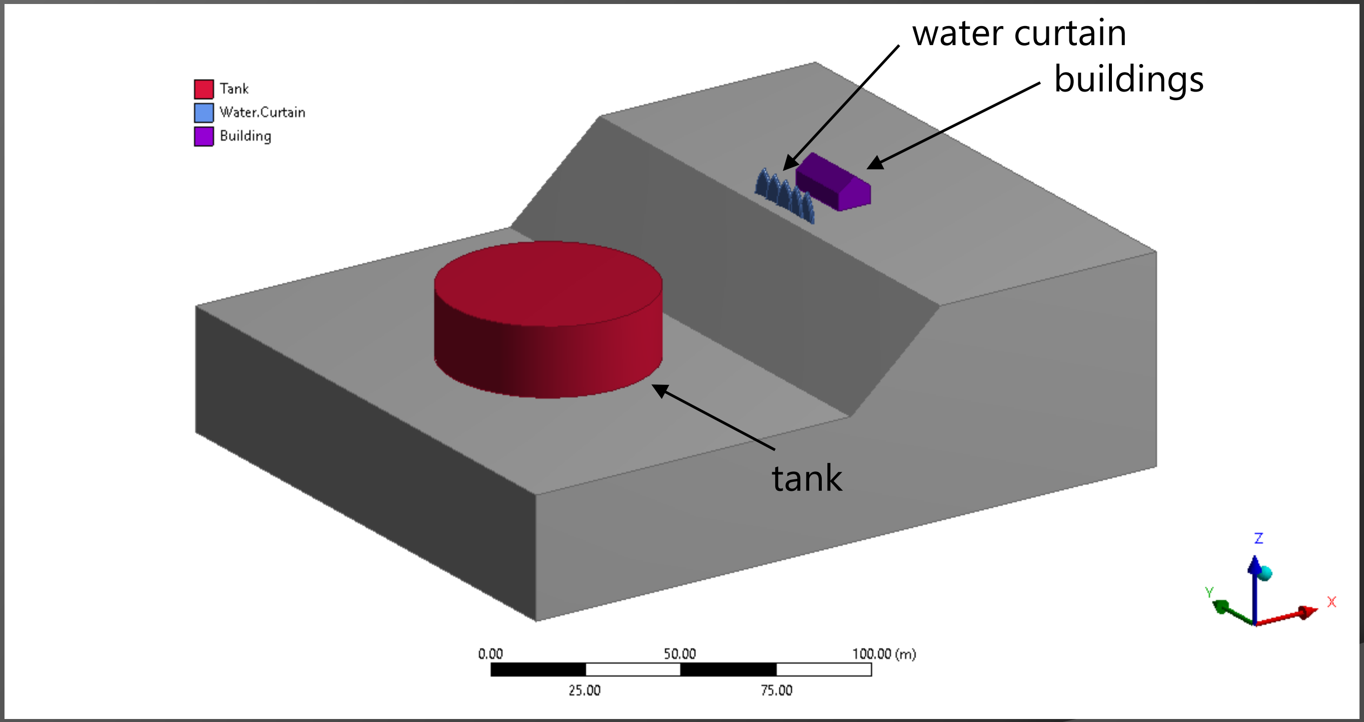


Figure 1: Layout of the fire source, water curtain and protected buildings

Introduction

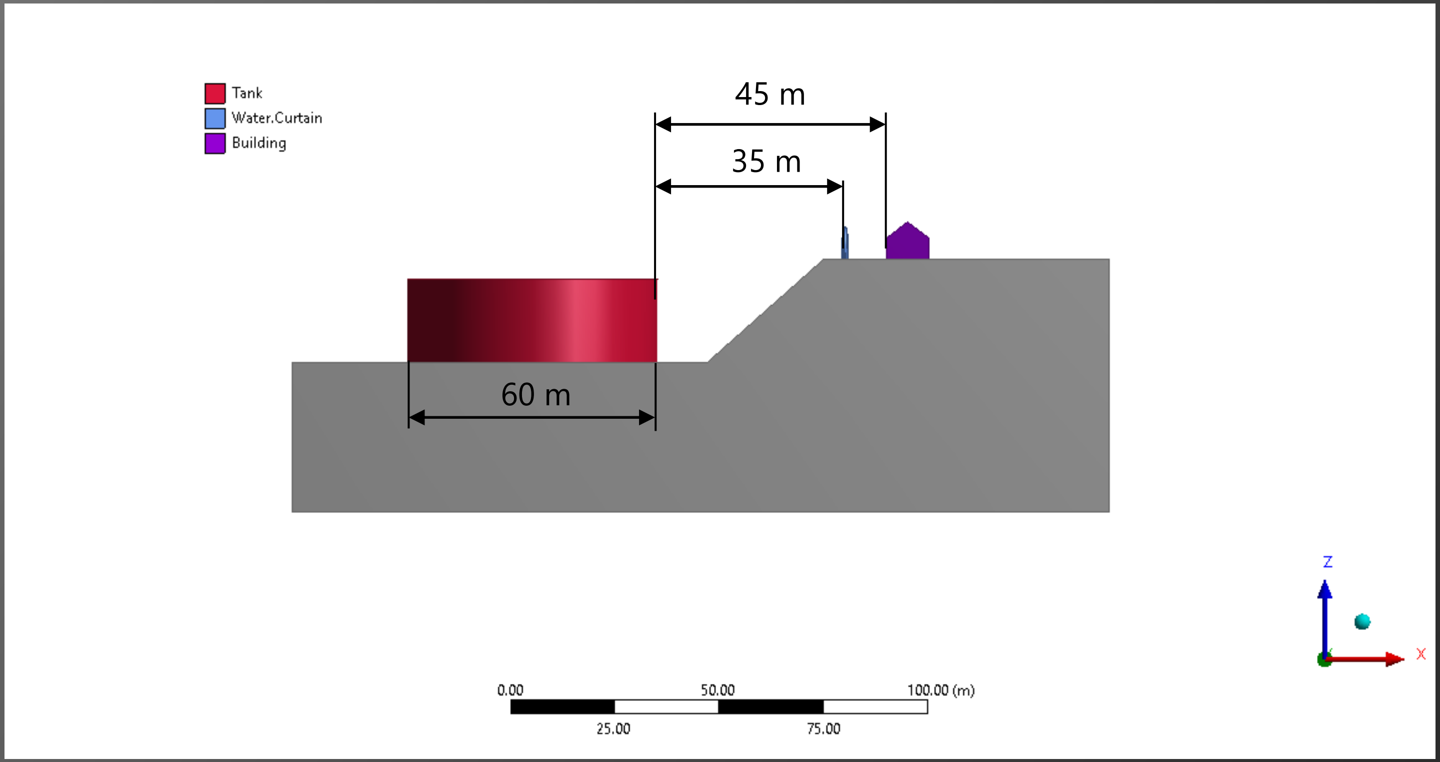


Figure 2: Dimensions and distances

- Insufficient performance using a single water curtain array

An additional study is required to characterise and understand the main parameters of the radiation heat shielding system!

System layout and operating parameters

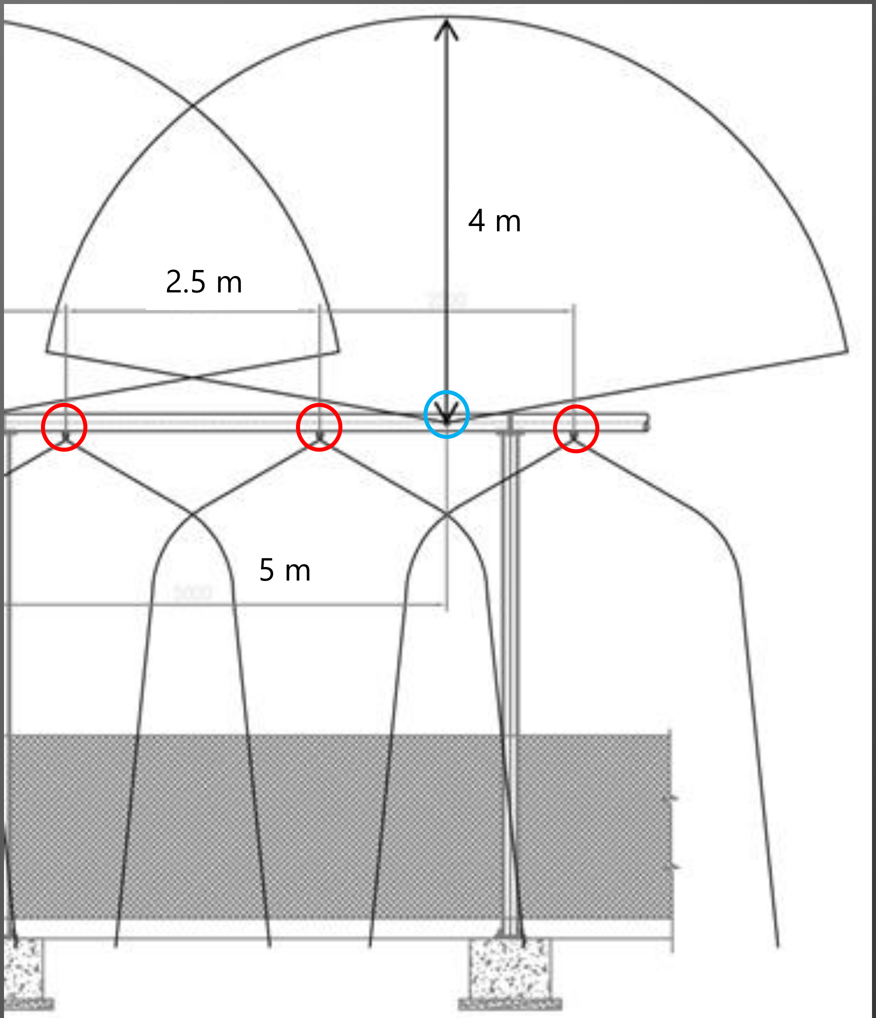


Figure 3: Layout sprinklers

- The water distribution pipe and nozzles elevation of 5 m
- 21 water curtain nozzles directed upward

  (5 m spacing, 92 l/min per head, 160° spray cone angle)
- 26 flat fan heads directed downward

  (2.5 m spacing, 63 l/min per head, 120° spray cone angle)

System layout and operating parameters

Two types of sprinklers used for the barrier:

- upper barrier: GW water curtain nozzle (www.gwsprinkler.com)
- lower barrier: PNR GX flat fan nozzle (www.pnr.eu/prodotti/gx)

Design and performance characteristics ambiguity of the utilised sprinklers

System layout and operating parameters

Additional data related to the system layout:

- Fuel tank diameter of 60 m
- Maximum irradiation heat flux of 20 kW/m^2
- Distance of interest 75 m from the origin (i.e. 45 m from the tank)
- Water curtain location approx. 10 m from the buildings (i.e. 35 m from the tank)

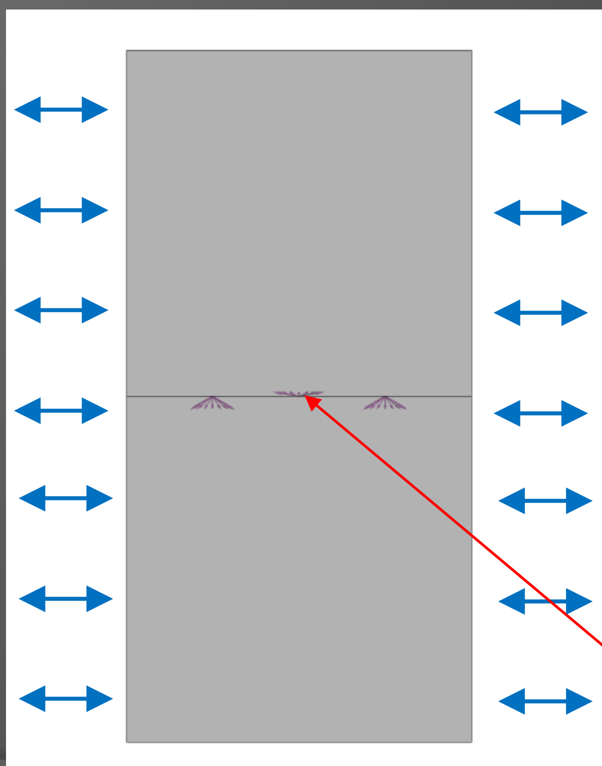
External conditions:

- Temperature of $12^{o}C$
- 75% relative humidity
- Initial zero wind conditions

Spray behaviour

CFD simulations to determine the most likely size of droplets and their speed

- representative section of the water curtain
- water nozzles in the mid-elevations
- periodic boundary conditions



periodic boundary conditions

water nozzles

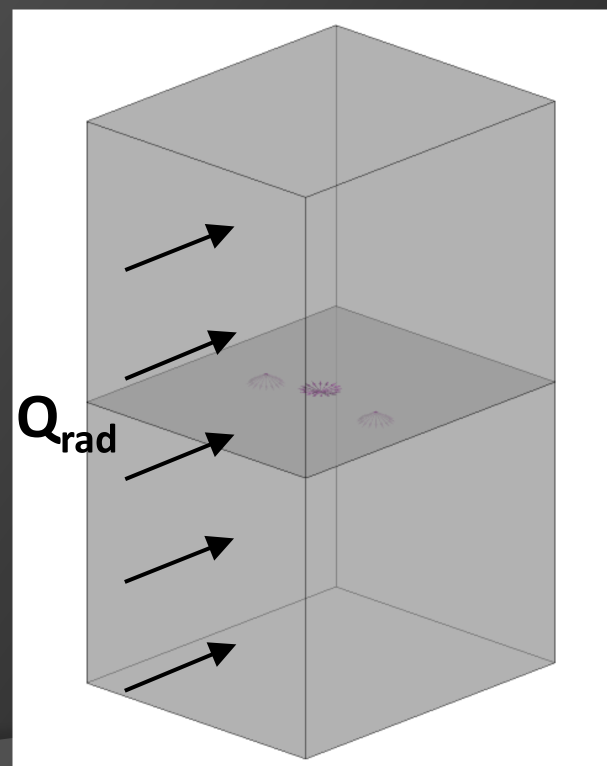


Figure 4: Simulation domain layout (periodic section)

Spray behaviour

- 5° spray rotation to avoid droplet collision
- spray coverage with 100% overlap

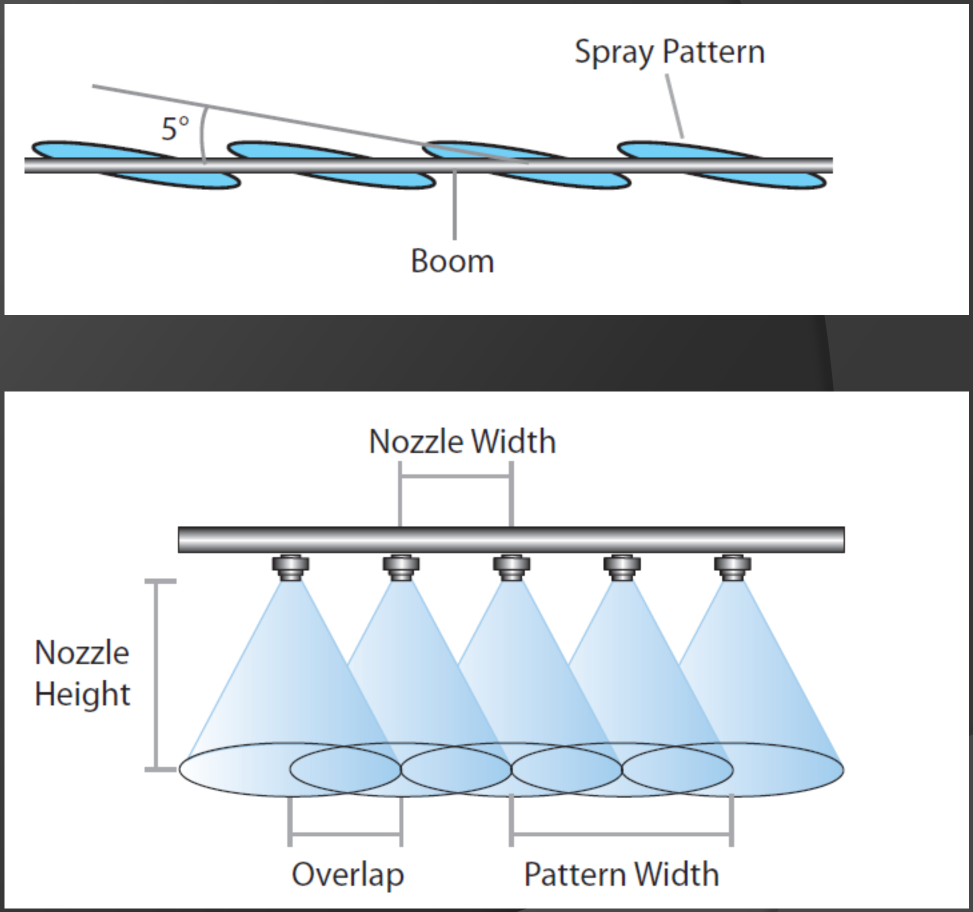


Figure 5: Spray arrangement [1]

Spray behaviour

Steady-state CFD simulations with 10000 particle tracks

Comparison with observations

- droplet diameter of 800 μm
- downward speed of 12 m/s
- upward speed of 20 m/s

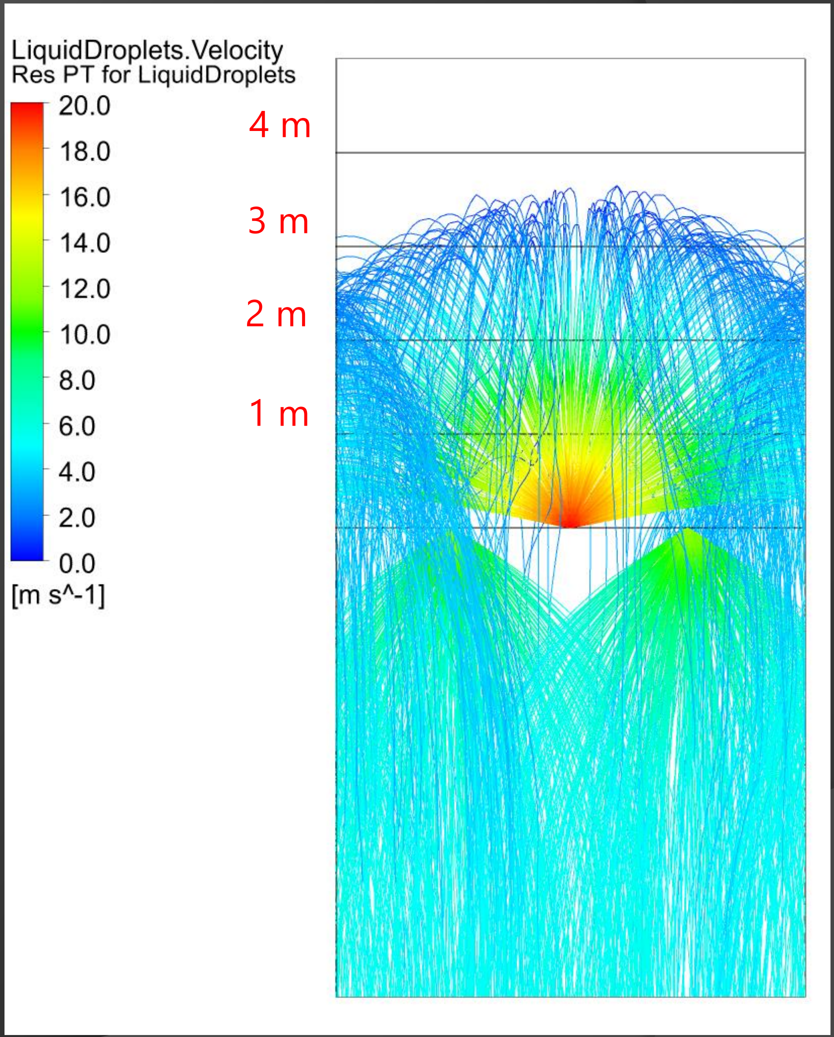


Figure 6: Particle tracks – injection speed of 12 and 20 m/s

Thermal radiation

Monte Carlo radiation model with 10 mil photon tracks

- Directional source equivalent to 20 kW/m^2 blackbody radiation at the tank wall
- Multigrey radiation model for the absorption and emission of the gaseous mixture
- Radiation absorptivity associated with spray droplets [2]:

$$\alpha_\lambda = 0.95[1 - exp(-0.875\xi_\lambda d)]$$

where $\xi_\lambda = 4\pi k_\lambda/\lambda$ and d is the droplet diameter

- Negligible effect of scattering

Thermal radiation

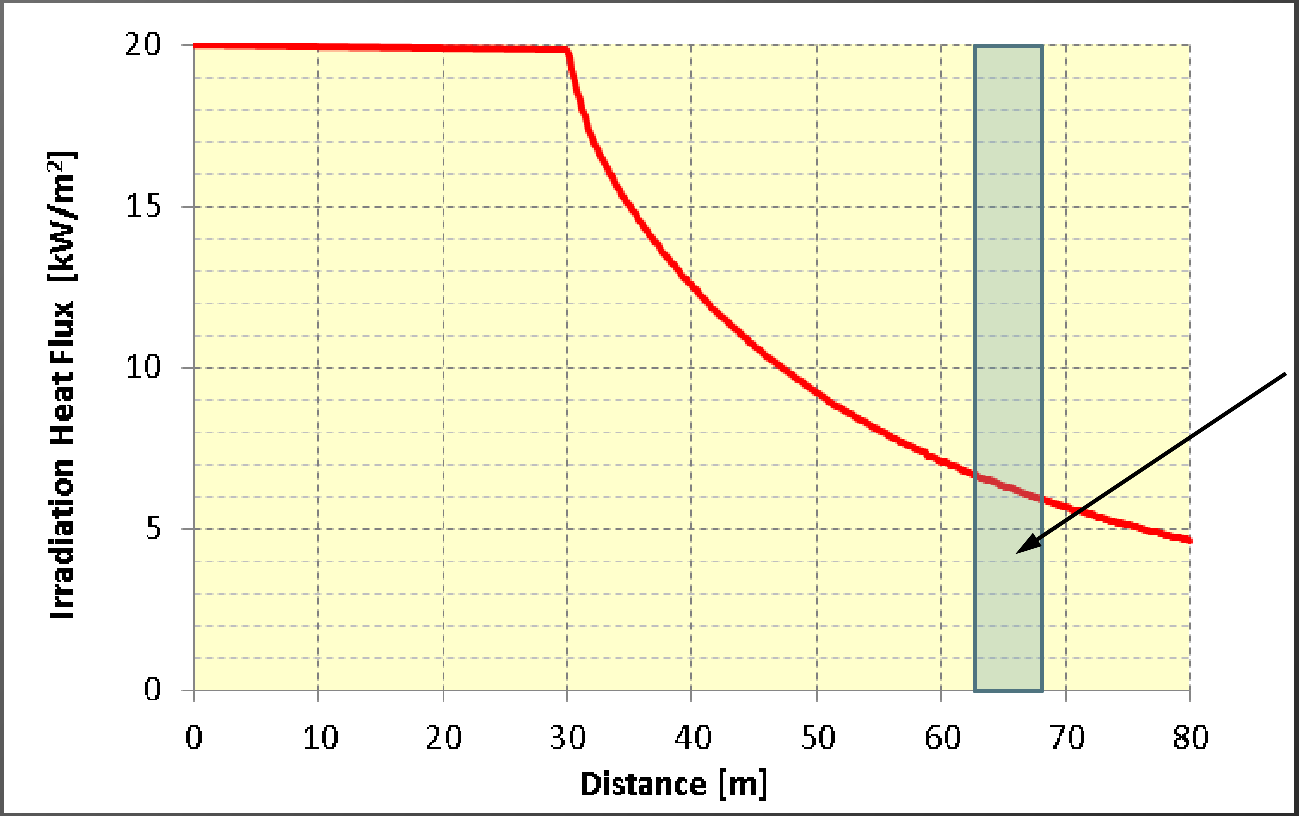
Attenuation of thermal radiation due to absorptivity (and emissivity) of

- liquid droplets produced by water sprays
- water vapour - high initial relative humidity (75%) or droplet evaporation

Modelling tasks conducted in the cylindrical coordinate system

Thermal radiation

Radiation attenuation in absence of the spray curtain



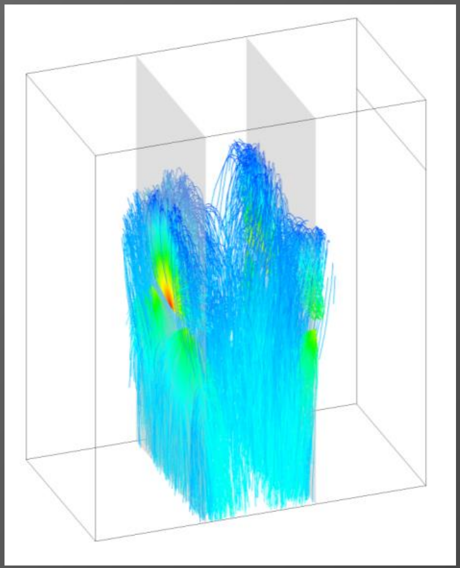
location of the periodic CFD simulation domain

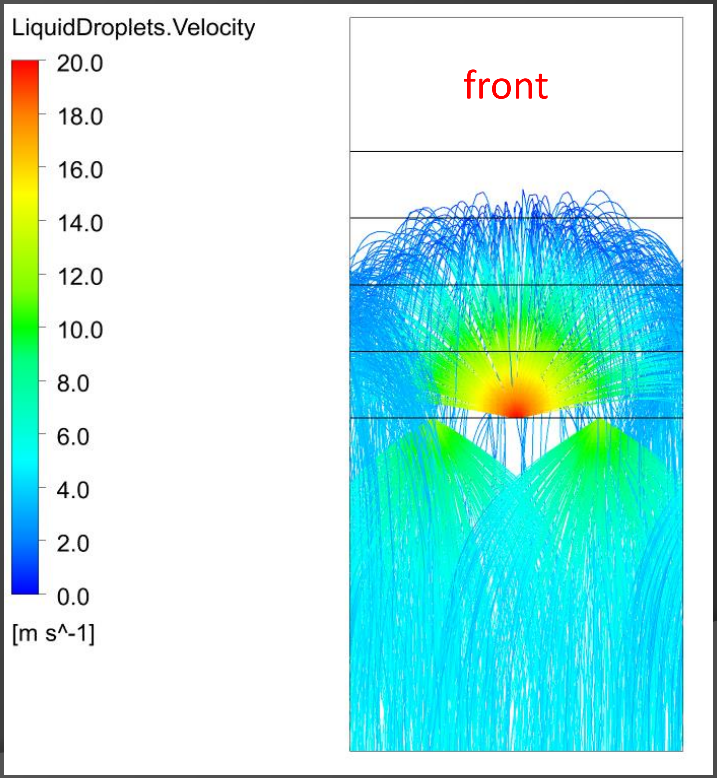
Figure 7: Radial distribution of the irradiation heat flux obtained with the multigrey model

Single and double water spray curtain

CFD simulations for a single and a double water spray curtain

- Particle tracks for the single water spray (Fig. 6)
- Particle tracks for a staggered arrangement of the double water spray curtain (Fig. 8)





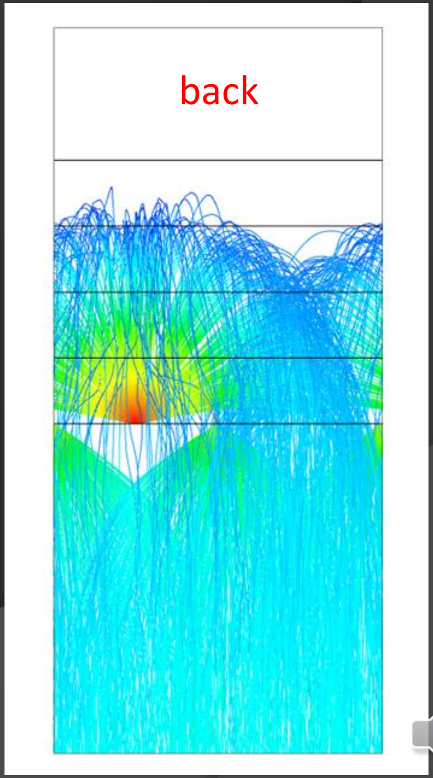


Figure 8: Particle trajectories of the double water spray curtain

Single and double water spray curtain

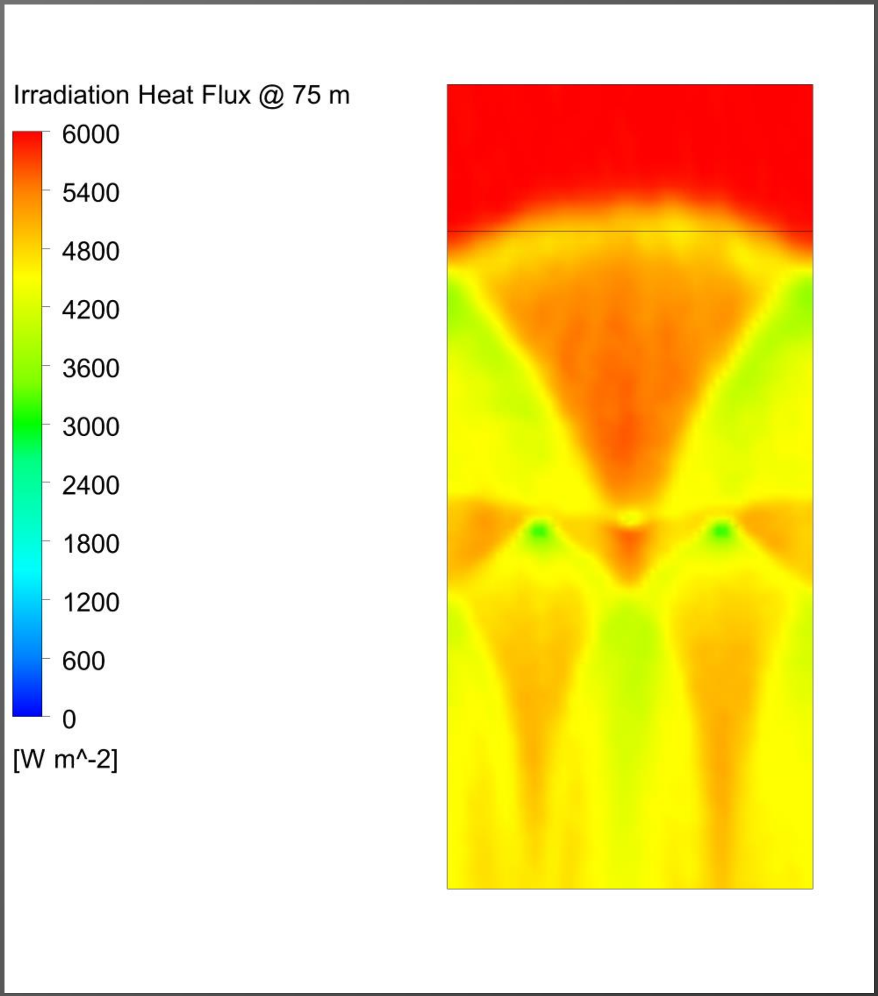


Figure 9: Irradiation heat flux for the single water spray curtain

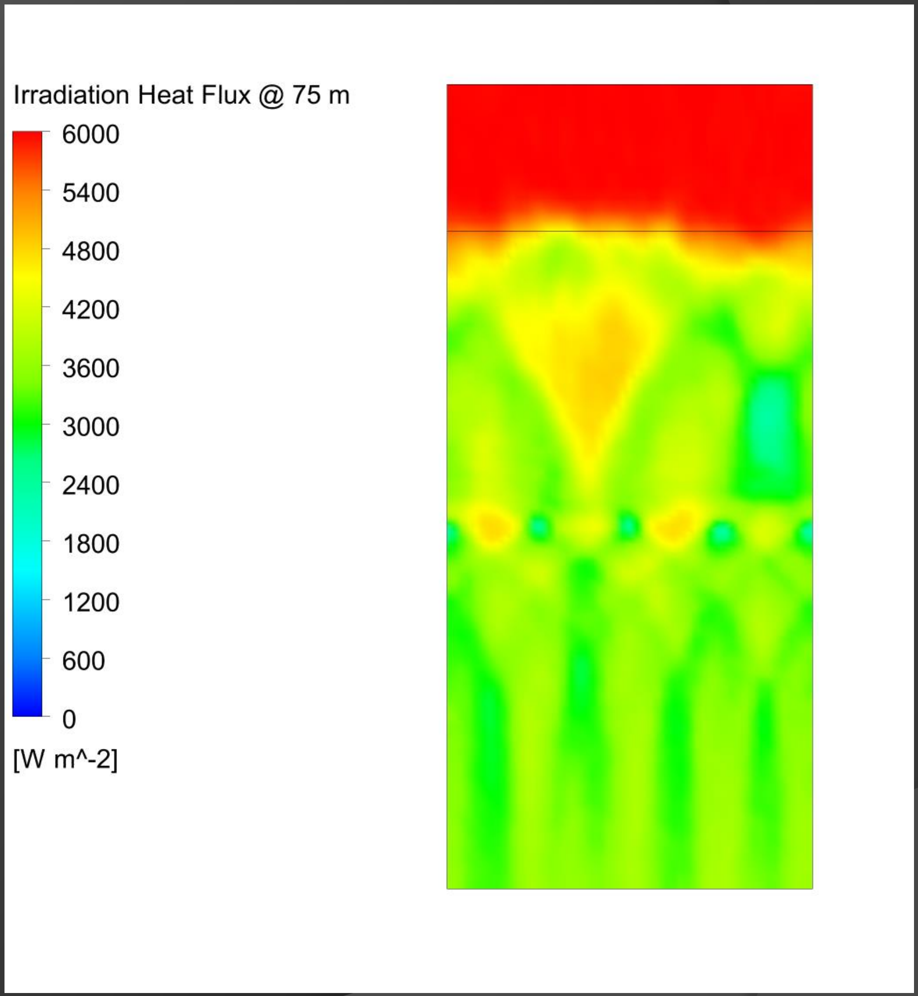


Figure 10: Irradiation heat flux for the double water spray curtain

Single and double water spray curtain

Averaged irradiated heat flux at the distance of 75 m from the origin:

- single water spray curtain: 4687 W/m^2
- double water spray curtain: 3674 W/m^2

Confidence in reducing the irradiation heat flux at the distance of 75 m below 3 kW/m^2

Parametric analysis

Algebraic modelling of the radiation attenuation to determine the required droplet size

- Definition of the radiation intensity based on

$$\frac{dI}{dx} = -\{(1 - r_{drop})\kappa_{amb} + r_{drop}\kappa_{drop}\}I$$

where

r_{drop} is volume fraction of droplets in the spray

κ_{amb} and κ_{drop} are ambient and droplet absorption coefficients

x is the radial distance from the source origin

Parametric analysis

- Calculation of the ambient absorption coefficient κ_{amb} using the Multigrey radiation model [11]

- Absorption coefficient of spray droplets [14]

$$\kappa_{drop} = \frac{1.5}{d}\alpha$$

where

α is the droplet radiation absorptivity

d is the droplet diameter

- Calculation of irradiation heat flux

$$q_{irrad} = \frac{I}{2\pi x}$$

Parametric analysis

Validation of the algebraic using the CFD result for a single spray curtain

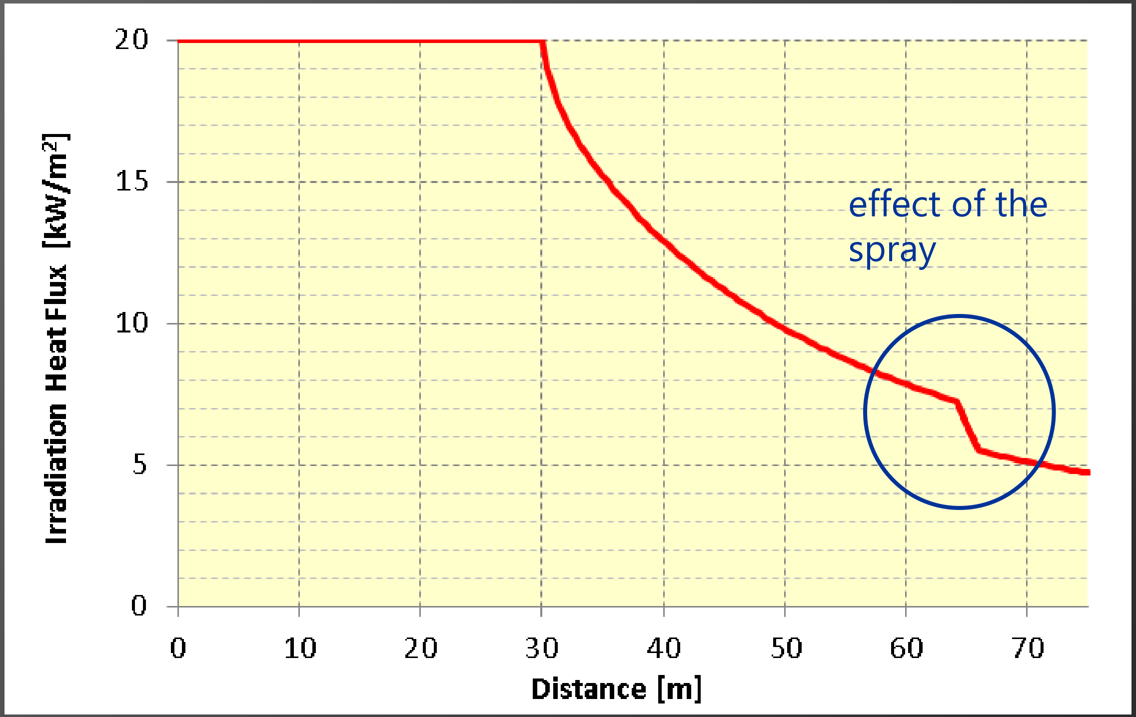


Figure 11: Radial variation of the irradiation heat flux (algebraic model)

Parametric analysis

- Calculation of the radiation distribution (Fig. 11) with the algebraic model for

  droplet diameter d = 800 μm

  droplet volume fraction r_{drop} = 0.015 %

  spray width x_{spray} = 2.0 m

- Droplet input parameters obtained directly from CFD simulation results

Irradiation heat flux at the distance of 75 m from the origin:

- algebraic model: 4713 W/m^2

- CFD simulation: 4687 W/m^2

Parametric analysis

Parametric analysis using the developed algebraic model:

- droplet diameter reduced from 800 to 200 μm
- constant liquid water flow rate of 63.0 + 92.0 + 63.0 l/min over 5 m long section

Parametric analysis

Avoiding the model dependence on the input parameters from the CFD simulations:

- Calculation of droplet speed (u) from the force balance:

$$\frac{1}{2} C_D \rho u^2 \left(\pi \frac{d^2}{4}\right) = (\rho_{liq} - \rho) g \left(\pi \frac{d^3}{6}\right)$$

where the droplet drag coefficient (C_D) is obtained via the Schiller-Neumann correlation

- Definition of the main attenuation parameter ($r_{drop}\ x_{spray}$) based on the mass conservation equation

$$\dot{m}_{liq} = \rho_{liq} u (r_{drop}\ x_{spray}) l_{sect}$$

where $\dot{m}_{liq}$ is the mass flow rate and l_{sect} is the length of the section (i.e. 5 m)

Parametric analysis

Reduction in the droplet diameter (d) causes:

- absorption coefficient (κ_{drop}) increase
- droplet speed (u) decrease
- main attenuation parameter ($r_{drop}\ x_{spray}$) increase

The droplet terminal speed (u) may lead to an overestimate of the radiation attenuation!

Parametric analysis

$d\ [\mu m]$	$u\ [m/s]$	$r_{drop}\ x_{spray}\ [m]$	$q_{irrad}\ [W/m^2]$
800	3.04	2.39E-04	4085
700	2.69	2.70E-04	3653
600	2.33	3.12E-04	3075
500	1.95	3.74E-04	2304
400	1.55	4.70E-04	1333
300	1.12	6.47E-04	380
200	0.68	1.08E-03	6

Table 1: Algebraic model – analysis results

- Desired level of irradiation for droplet diameter below 500 μm
- Increased number of smaller nozzles (with lower flow rate) per unit length

Operating parameters of the improved system

- CFD simulations for the droplet diameters of 500, 400 and 300 μm
- Doubling the number of nozzles & halving the water flow rate per nozzle

Heads directed upward:

- 1/2 · 5.0 m spacing
- nominal flow rate 1/2 · 92 l/min per head

Heads directed downward:

- 1/2 · 2.5 m spacing
- nominal flow rate 1/2 · 63 l/min per head

Operating parameters of the improved system

- Vertical elevation increase for the frame with nozzles from 5 to 6.5 m
- Unchanged initial droplet speed - 12 m/s for the downward sprays, and 28 m/s for the upward sprays

Operating parameters of the improved system

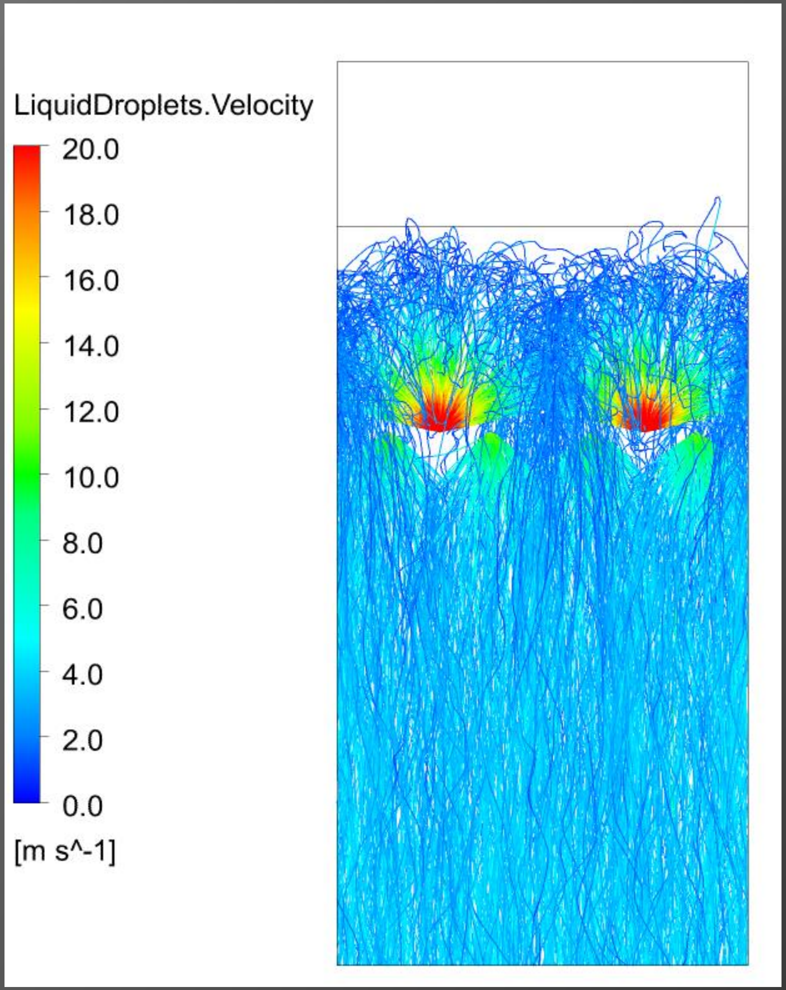


Figure 12: Particle trajectories for droplet diameter of 300 μm

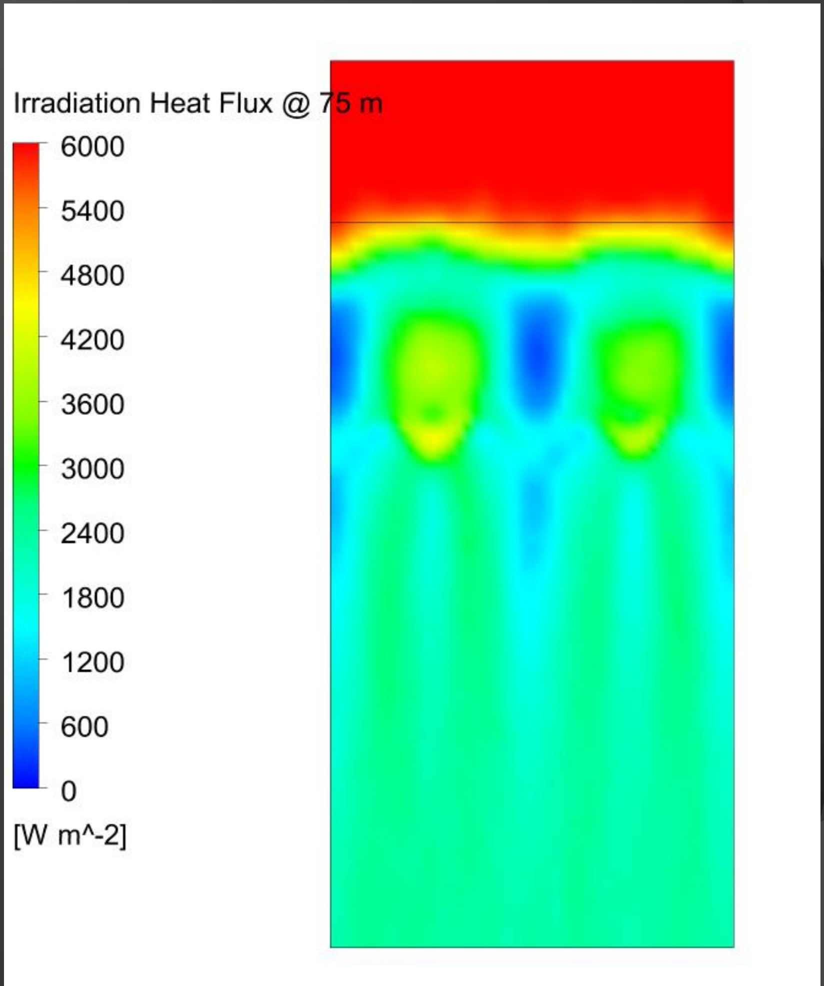
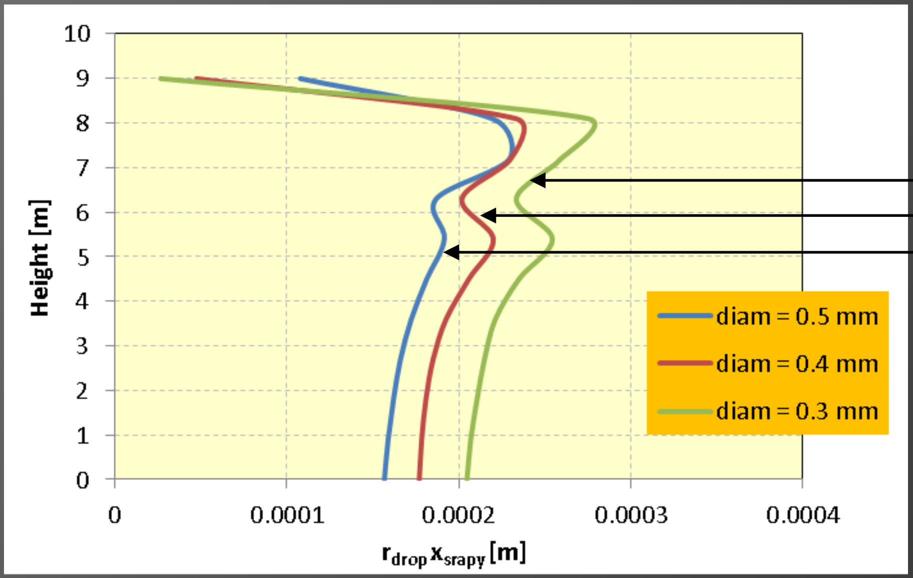


Figure 13: Irradiation heat flux for droplet diameter of 300 μm

Operating parameters of the improved system



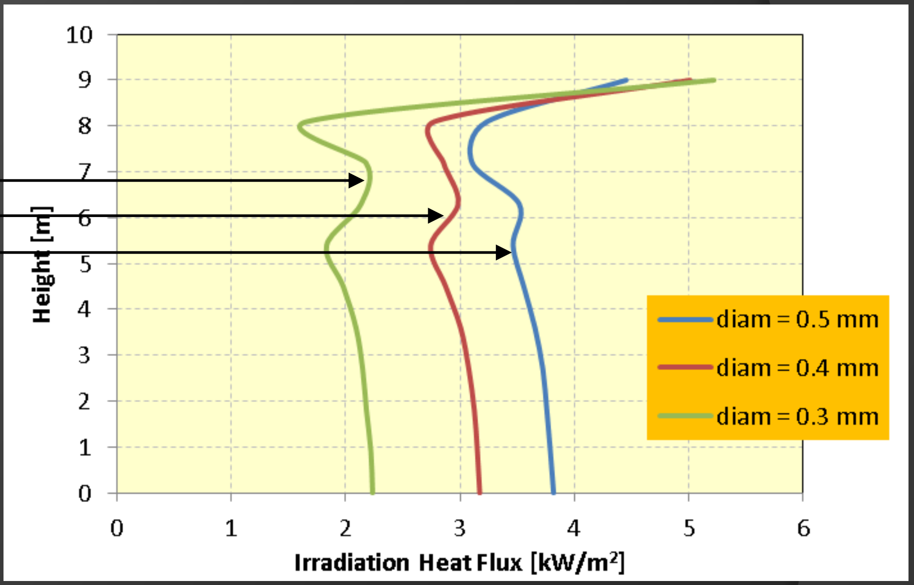


Figure 14: Vertical distribution of the main attenuation parameter $r_{drop}\ x_{spray}$

Figure 15: Vertical distribution of irradiation heat flux @ 75 m

Conclusions and recommendations

Average irradiation heat flux at 75 m from the origin

$d\ [\mu m]$	$q_{irrad}\ [W/m^2]$
500	3577
400	3020
300	2184

Table 2: CFD results of the improved system

- Reduction of the droplet diameter to 400 μm for a single curtain system & raising the nozzles to 6.5 m
- Necessity of a double curtain system for larger droplet sizes

Thank you !

Contact information

Dr Andrei Horvat

Phone: +44 1235 819 729

Mobile: +44 79 72 17 27 00

Skype: a.horvat

E-mail: mail@caspus.co.uk

Web: www.caspus.co.uk

References

1. R. Grisso, P. Hopkins, S.D. Askew, L. Hipkins, D. Maccall, Nozzles: selections and sizing, Virginia Tech, Virginia State University, Publication 442-032
2. J.S. Truelove, RD2: Data and reference sources on emissivity of gases, HTFS Handbook, 1991
3. M. F. Modest, Radiative Heat Transfer, Academic Press, 2003, p. 341
4. P. H. Thomas, Absorption and scattering of radiation by water sprays of large drops, J. Appl. Phys, 1952, 3, pp. 385-393.
5. L. A. Dombrovsky, S. Dembele, J.X. Wen, Shielding of fire radiation with the use of multi-layered water mist curtains: preliminary estimates, Comp. Thermal Sciences, 2016, 8 (4), pp. 371-380.