Water Spray Curtain for Shielding Hydrogen Flames – Effect of Flame Spectrum on Total Transmissivities

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Outline

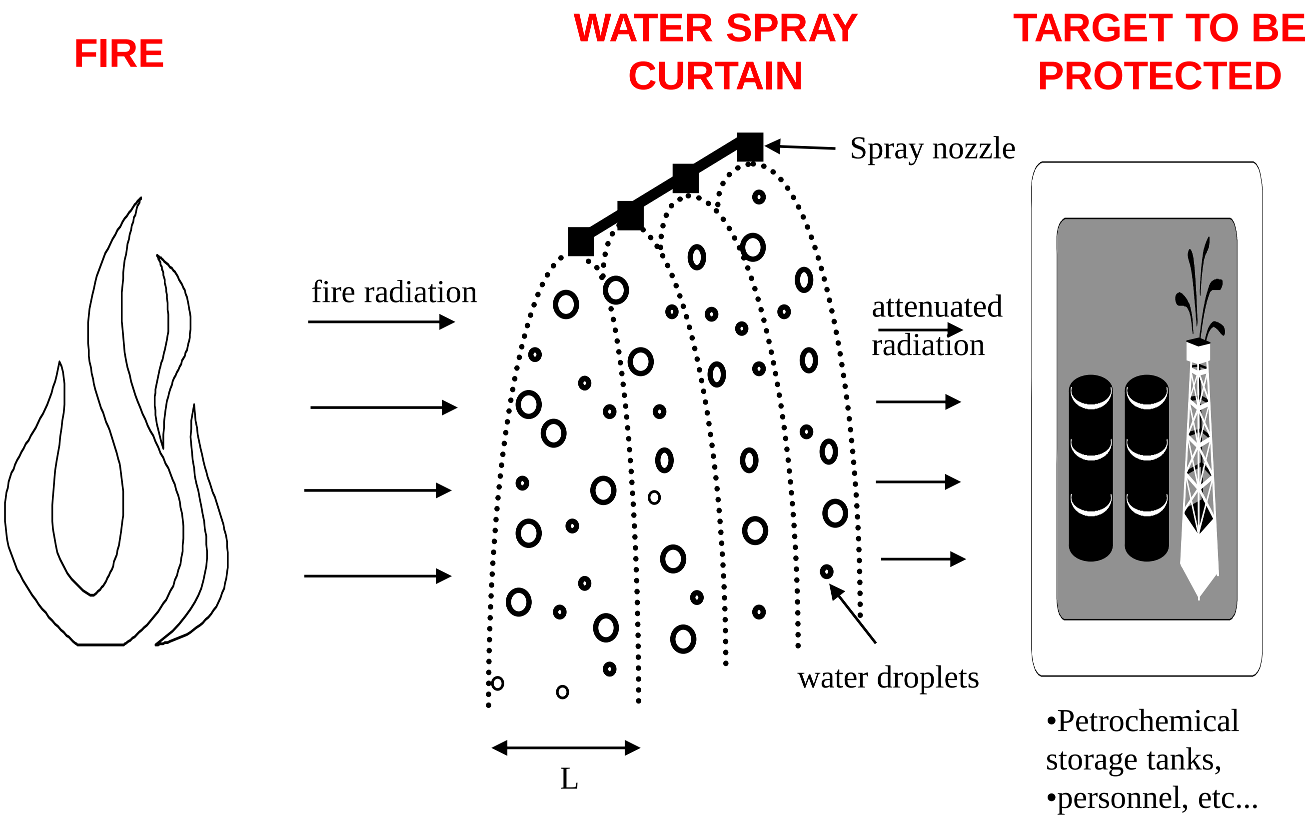
- Background
- Objectives
- Methodology
- Results & Discussions
- Conclusions

Background

- In the event of accidental fires, water spray curtain could be an effective means for shielding and attenuating fire thermal radiation to safe levels

- The technique could be used to protect personnel, as evacuation means, protect structures, flammable hydrocarbon storage tanks etc…

- Typical permissible heat flux 1.6 kW/m^2 (personnel), 16 kW/m^2 (integrity of structures)



Source: S. Dembele, J. Wen, JF Sacadura, "Analysis of the two-flux model for predicting water spray transmittance in fire protection application" *ASME Journal of Heat Transfer*, 122(1), pp. 183-186 (2000).

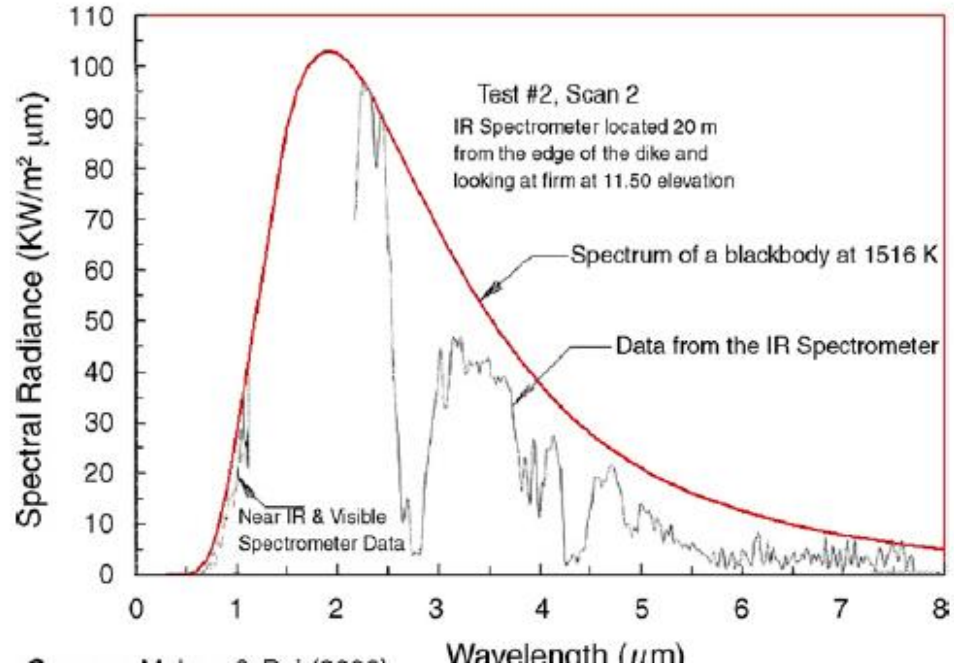
AIM IS NOT TO EXTINGUISH OR SUPPRESS THE FIRE IN SHIELDING/CURTAIN APPLICATIONS !

- Transmissivity of the water spray curtain is the most practical information to quantify its attenuation efficiency – but depends on incident flame spectrum

- For transmissivity calculations, literature studies are based on hydrocarbon flames with assumption of a blackbody incident spectrum (emissivity $\varepsilon_\lambda=1$) to simplify calculations

- For hydrocarbon fires, blackbody emission spectrum acceptable for optically thick sooty flames (soot continuous emission dominant over gaseous H_2O, CO_2, CO banded emission)

35 m diameter LNG pool fires (Montoir Tests 1987)…



Source: NEDELKA D., MOORHOUSE J., TUCKER R.F. The Montoir 35 m diameter LNG pool fire experiments. *Liquefied Natural Gas-9 Congress, Nice, October 17-20 1989*.

…blackbody emission spectrum acceptable

Water spray curtain – 3m gasoline pool fires…

European Project ASTRRE (1994-1998) – water spray curtains for shielding fire thermal radiation

Source: S. Dembele. Modelisation et etude experimentale des transferts de chaleurs dans un rideau d'eau - PhD Thesis – INSA Lyon- France, 1998.

…spray curtain transmissivity based on assumption of blackbody incident spectrum at flame temperature

What about Hydrogen flames?

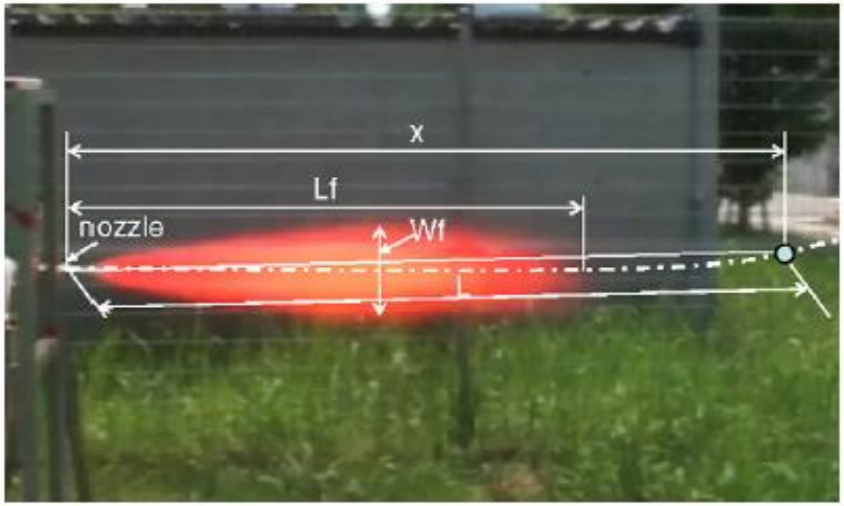
- Worldwide interest in hydrogen energy because of its environmental benefits

- Many research studies to assess safety hazards of hydrogen fires

- Protection against H_2 flames using barrier walls suggested by Schefer et al., IJHE vol.33, 2008

- Use of water spray curtain for shielding hydrogen flame radiation not reported in literature

Emission spectrum of Hydrogen diffusion flames

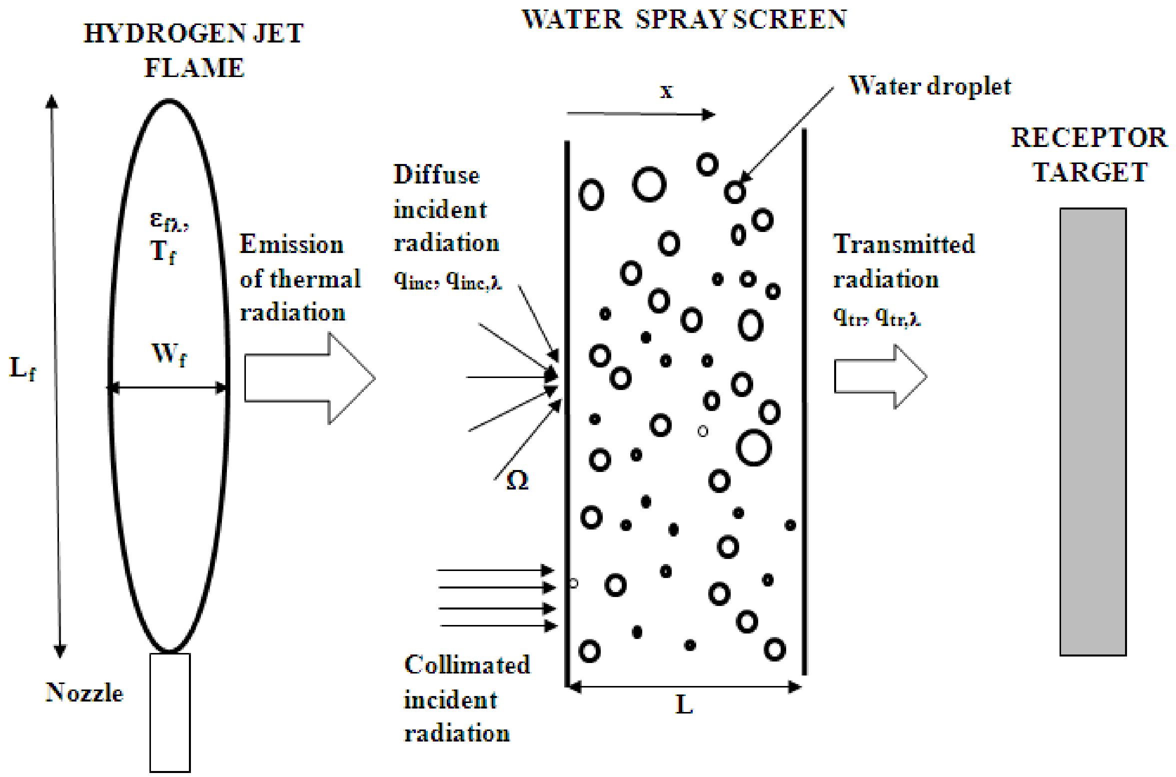


Source: Imamura et al. Experimental investigation on the thermal properties of hydrogen jet flame and hot currents in the downstream region. Int J Hydrogen Energy 2008; 33:3426-35.

Hydrogen flame made visible by flame reaction with sprayed NaCl solution

- Hydrogen flame barely visible, non-sooty
- Radiant emission mainly due gaseous water vapour H_2O in the infrared spectral region

Using water spray curtain for shielding hydrogen flames



- ❖ **Assumption of flame blackbody emission spectrum (which simplifies transmissivity calculations) strictly not valid !**
- ❖ **Published literature transmissivities data based on incident blackbody spectrum cannot be employed for hydrogen flames**

Objectives

- Propose a methodology to calculate the spectral and total transmissivities of water spray curtains in shielding radiation from hydrogen flames using the actual/real H_2 flame spectrum

- Investigate quantitatively the validity of the assumption of simplified blackbody incident spectrum in evaluating transmissivities by comparison with the actual H_2 flame spectrum data

Methodology

❖ Spectral Transmissivity of the water spray curtain

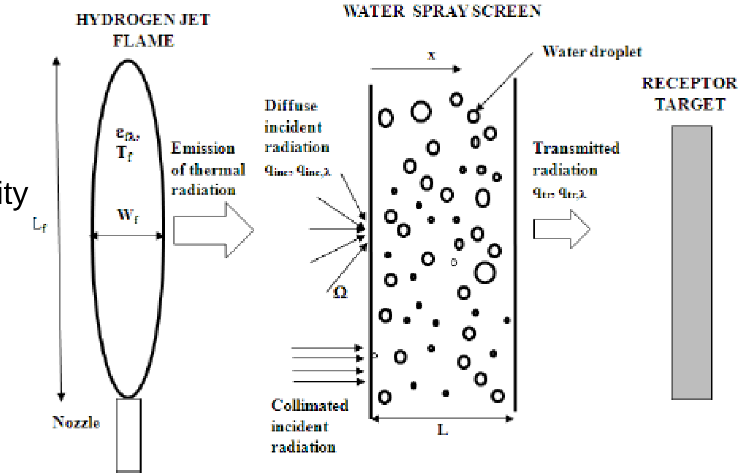
$$\tau_{ws,\lambda} = \frac{q_{tr,\lambda}}{q_{inc,\lambda}} = \frac{q_{tr,\lambda}}{\psi_\lambda F_v \varepsilon_{f\lambda} \pi I_{b\lambda}(T_f)}$$

F_v : view factor
T_f: flame temperature

ψ_λ :atmospheric transmissivity from flame to curtain

$$I_{b\lambda}(T_f) = \frac{C_1 / \pi}{\lambda^5\left(\exp[C_2/(\lambda T_f)] - 1\right)}$$

:Blackbody intensity (Planck's function)



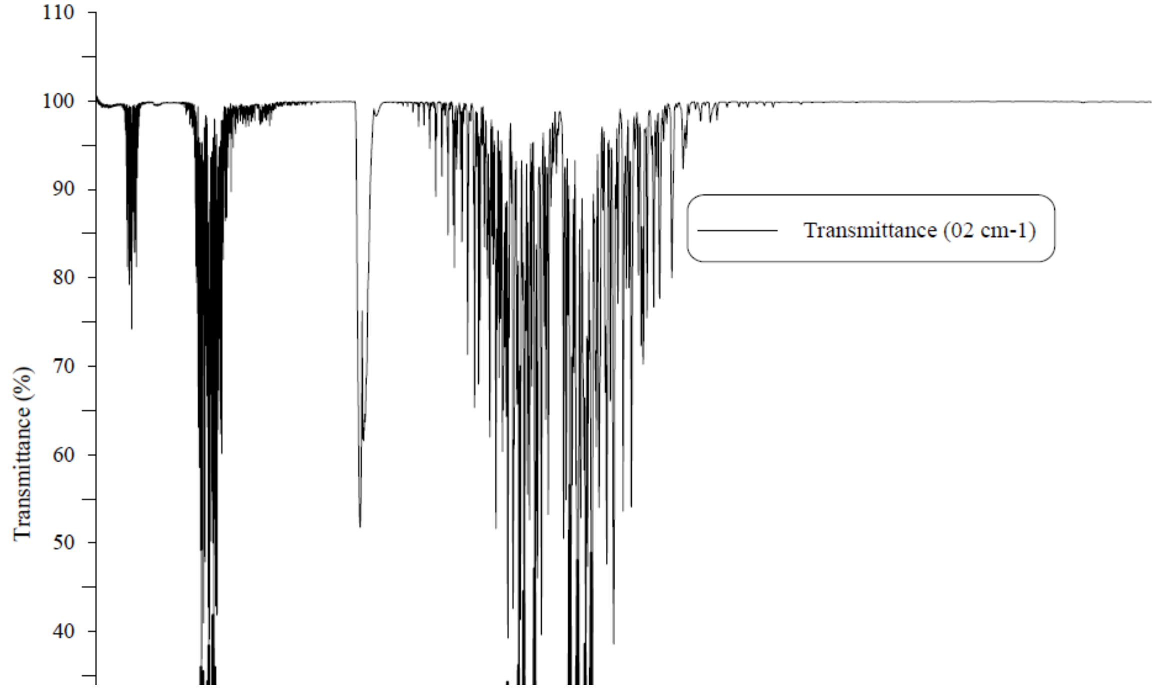
❖ **Additional complexity: model the flame gaseous H_2O spectral emissivity $\varepsilon_{f\lambda}$**

❖ Total Transmissivity of the water spray curtain

$$\tau_{ws} = \frac{q_{tr}}{q_{inc}} = \frac{\int_0^\infty q_{tr,\lambda} d\lambda}{\int_0^\infty q_{inc,\lambda} d\lambda} = \frac{\int_0^\infty \tau_{ws,\lambda} q_{inc,\lambda} d\lambda}{\int_0^\infty q_{inc,\lambda} d\lambda} = \frac{\int_0^\infty \tau_{ws,\lambda} \psi_\lambda F_v \varepsilon_{f\lambda} \pi I_{b\lambda}(T_f) d\lambda}{\int_0^\infty \psi_\lambda F_v \varepsilon_{f\lambda} \pi I_{b\lambda}(T_f) d\lambda} = \frac{\int_0^\infty \tau_{ws,\lambda} \psi_\lambda \varepsilon_{f\lambda} I_{b\lambda}(T_f) d\lambda}{\int_0^\infty \psi_\lambda \varepsilon_{f\lambda} I_{b\lambda}(T_f) d\lambda}$$

❖ **For transmissivity calculation assuming blackbody spectrum : $\varepsilon_{f\lambda}=1$**

Modelling the spectral emissivity of hydrogen flames (gaseous H_2O)



Source: S. Dembele. Modelisation et etude experimentale des transferts de chaleurs dans un rideau d'eau - PhD Thesis – Lyon-France, 1998.

- **Emission/absorption of H_2O in specific bands (not continuous like soot)**
- **Large number of vibration-rotation transition lines in H_2O spectrum:** **LINE-BY-LINE SPECTRAL ANALYSIS IMPRACTICAL DUE TO LARGE COMPUTING TIME**

Modelling the spectral emissivity of hydrogen flames (gaseous H_2O)

NARROW BAND STATISTICAL GAS RADIATION MODEL APPROACH ADOPTED FOR SPECTRAL EMISSIVITY CALCULATIONS

(averaging properties over spectral narrow band)

$$\bar{\varepsilon}_{f\lambda} = \frac{1}{\Delta\nu}\int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} \varepsilon_{f\lambda} d\nu = \frac{1}{\Delta\nu}\int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} [1-\exp(-k_{f\lambda}.L_m)] d\nu = \frac{1}{\Delta\nu}\int_{\nu-\Delta\nu/2}^{\nu+\Delta\nu/2} [1-\tau_{f\lambda}] d\nu = 1-\bar{\tau}_{f\lambda} = \bar{\alpha}_{f\lambda}$$

$$\bar{\tau}_{f\lambda} = \frac{1}{\Delta\nu}\int_{\Delta\nu} \exp\left[-k_{f\lambda}.L_m\right] d\nu = \exp\left[-\frac{\bar{\beta}_\nu}{\pi}\left(\sqrt{1+\frac{2\pi\chi_{H_2O}PL_m\bar{k}_\nu}{\bar{\beta}_\nu}}-1\right)\right]$$

L_m: mean-beam length of hydrogen flame calculated using correlations for hydrogen jet flames

Further details of models in: **S. Dembele & J.X. Wen.** Analysis of the screening of hydrogen flares and flames thermal radiation with water sprays – International Journal of Hydrogen Energy (2013, in PRESS).

Modelling radiative heat transfer in water sprays

$$\mu \frac{dI_\lambda(x,\mu)}{\beta_{d\lambda} dx} + I_\lambda(x,\mu) = (1-\omega_{d\lambda}) I_{b\lambda}[T_{spray}] + \frac{\omega_\lambda}{2} \int_{-1}^{1} \varphi_{d\lambda}(\mu,\mu') I_\lambda(x,\mu') d\mu' = S_\lambda(x,\mu)$$

RADIATIVE TRANSFER EQUATION

- ❖ **Thermal radiation attenuation by water droplets due to absorption and scattering**
- ❖ **Water droplet spectral properties (absorption and scattering coefficients, phase function calculated from Mie theory**
- ❖ **The radiative transfer equation solved with the TWO-FLUX method (intermediate level of difficulty compared to Discrete Ordinates Method or Finite Volume Method)**

Results and Discussion

Scenarios studied: Hydrogen flame

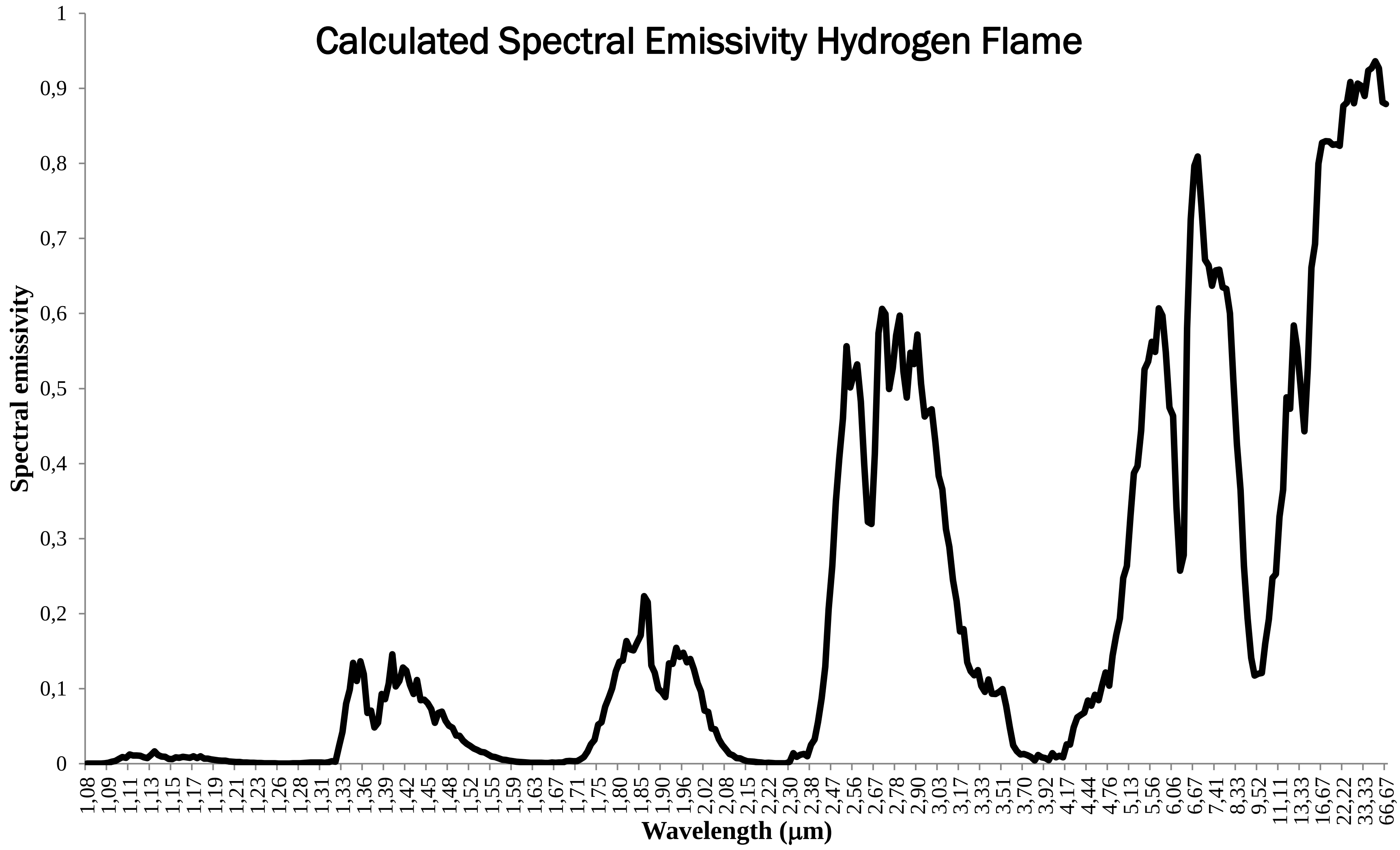
	Hydrogen jet Diffusion Flame
Nozzle diameter (mm)	2
Flame length L_f (m)	4.9
Flame width W_f (m)	0.8
Temperature (K)	1600
Molar fraction H_2O	0.35
Molar fraction N_2	0.65

Flame investigated experimentally by: Mogi T, Horiguchi S. Experimental study on the hazards of high-pressure hydrogen jet diffusion flames. J Loss Prev Process Ind 2009; 22:45–51

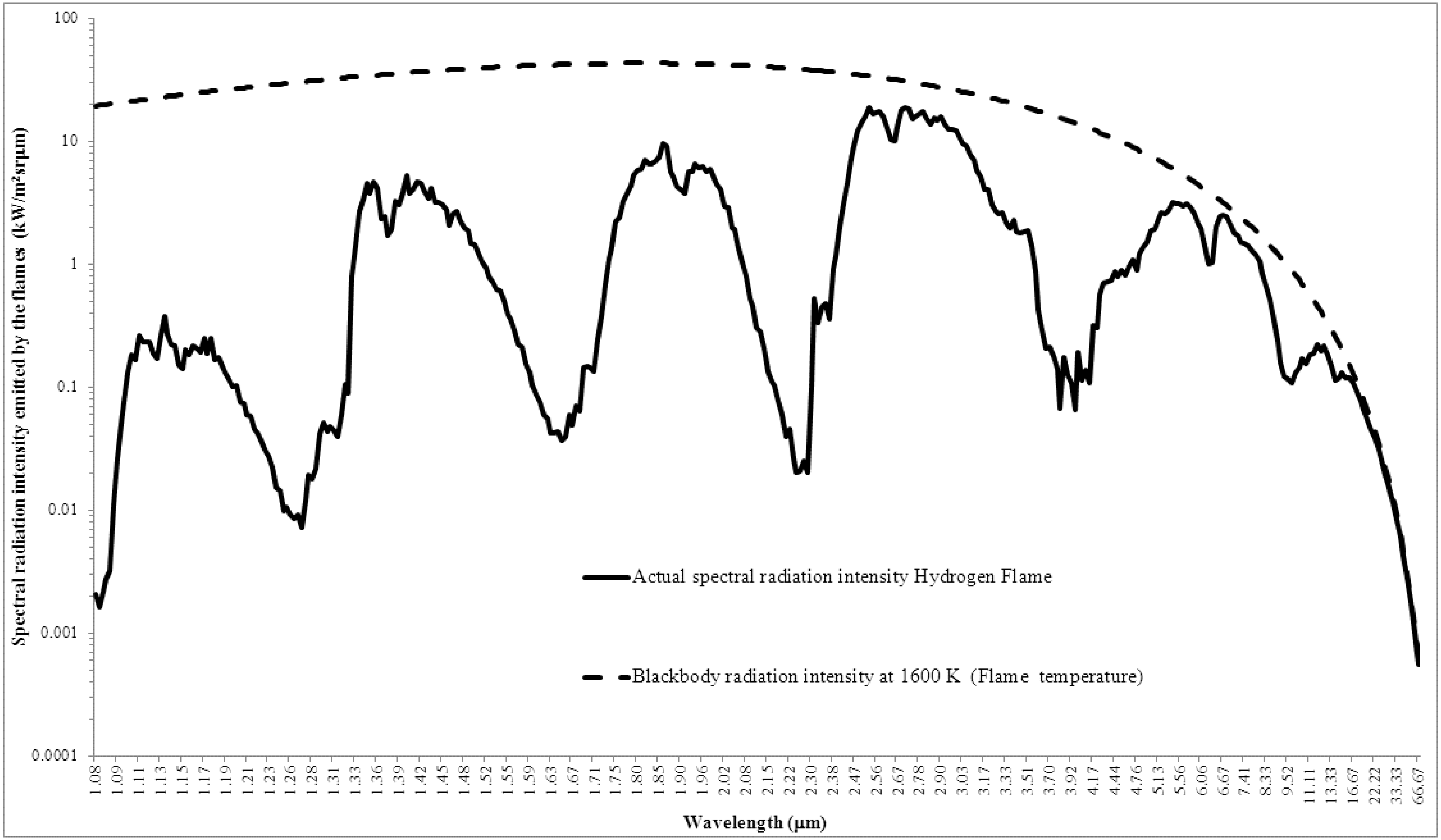
Scenarios studied: water spray curtain

	Mean droplet diameter d_d (mm)	Droplet mass loading C_d (kg/m^3)	Water screen thickness, L(m)
Water spray curtain 1	100	0.1	0.5
Water spray curtain 2	100	0.2	0.5
Water spray curtain 3	100	0.1	1
Water spray curtain 4	100	0.2	1
Water spray curtain 5	300	0.1	0.5
Water spray curtain 6	300	0.2	0.5
Water spray curtain 7	300	0.1	1
Water spray curtain 8	300	0.2	1
Water spray curtain 9	500	0.1	0.5
Water spray curtain 10	500	0.2	0.5
Water spray curtain 11	500	0.1	1
Water spray curtain 12	500	0.2	1

Model verification studies carried out.


Calculated Spectral Emissivity Hydrogen Flame
Spectral emissivity
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1,08 1,09 1,11 1,13 1,15 1,17 1,19 1,21 1,23 1,26 1,28 1,31 1,33 1,36 1,39 1,42 1,45 1,48 1,52 1,55 1,59 1,63 1,67 1,71 1,75 1,80 1,85 1,90 1,96 2,02 2,08 2,15 2,22 2,30 2,38 2,47 2,56 2,67 2,78 2,90 3,03 3,17 3,33 3,51 3,70 3,92 4,17 4,44 4,76 5,13 5,56 6,06 6,67 7,41 8,33 9,52 11,11 13,33 16,67 22,22 33,33 66,67
Wavelength (μm)

Thermal radiation spectrum from hydrogen flame that is incident on the water spray curtain

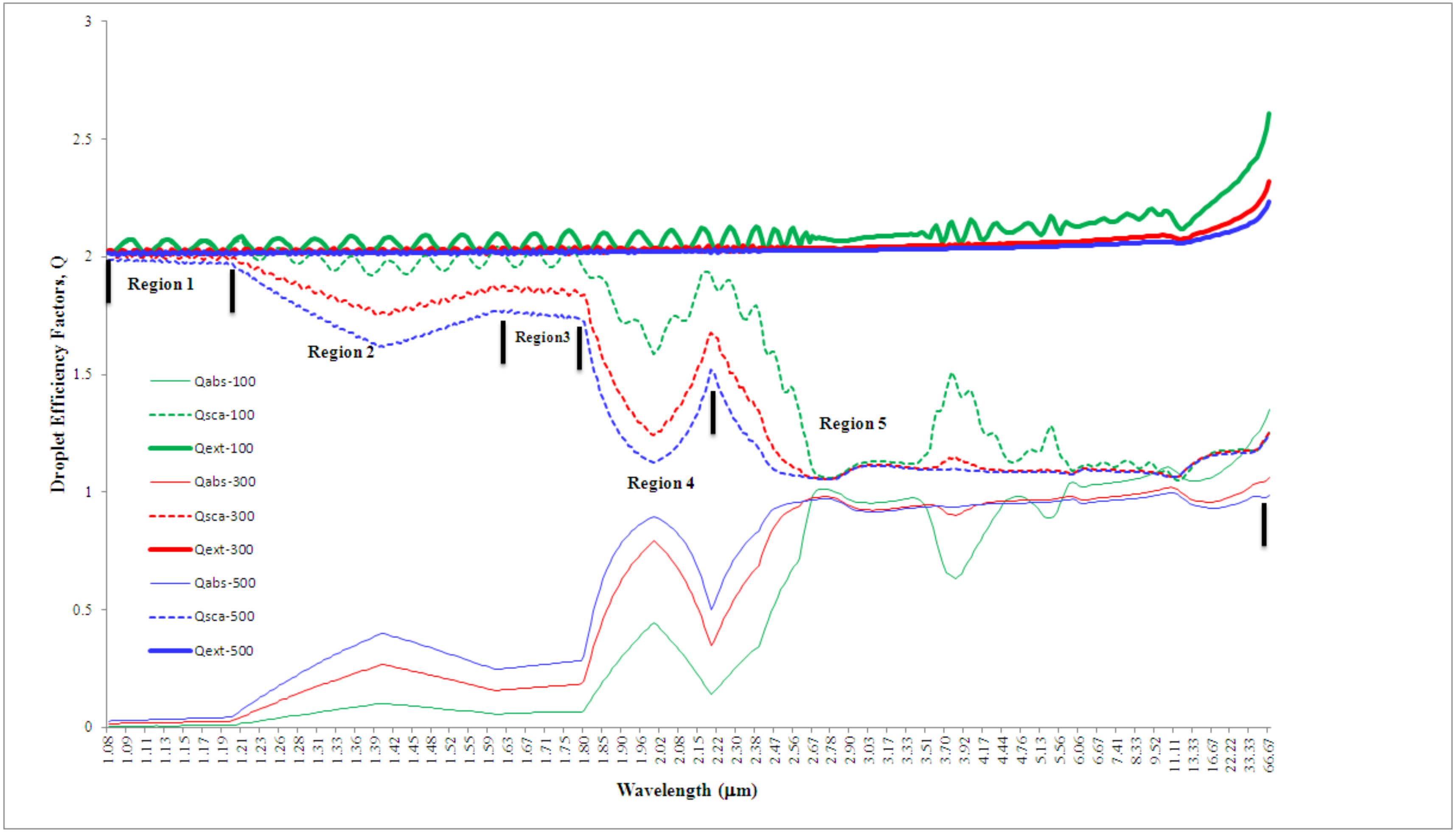


Comparative results of total transmissivities

	Curtain optical thickness	Water spray curtain total transmissivity (%)		
		Actual H_2 spectrum	Blackbody spectrum	Ratio Blackbody/Actual
Water curtain 1 (100)	1.6	26.4	40.6	1.5
Water curtain 2	3.1	8.6	21.3	2.5
Water curtain 3	3.1	8.6	21.3	2.5
Water curtain 4	6.3	2	9	4.5
Water curtain 5 (300)	0.5	62	68.5	1.1
Water curtain 6	1	38.8	48	1.2
Water curtain 7	1	38.8	48	1.2
Water curtain 8	2	15.6	25.5	1.6
Water curtain 9 (500)	0.3	74.8	78.4	1.1
Water curtain 10	0.6	56.1	61.8	1.1
Water curtain 11	0.6	56.1	61.8	1.1
Water curtain 12	1.2	31.7	39.3	1.2

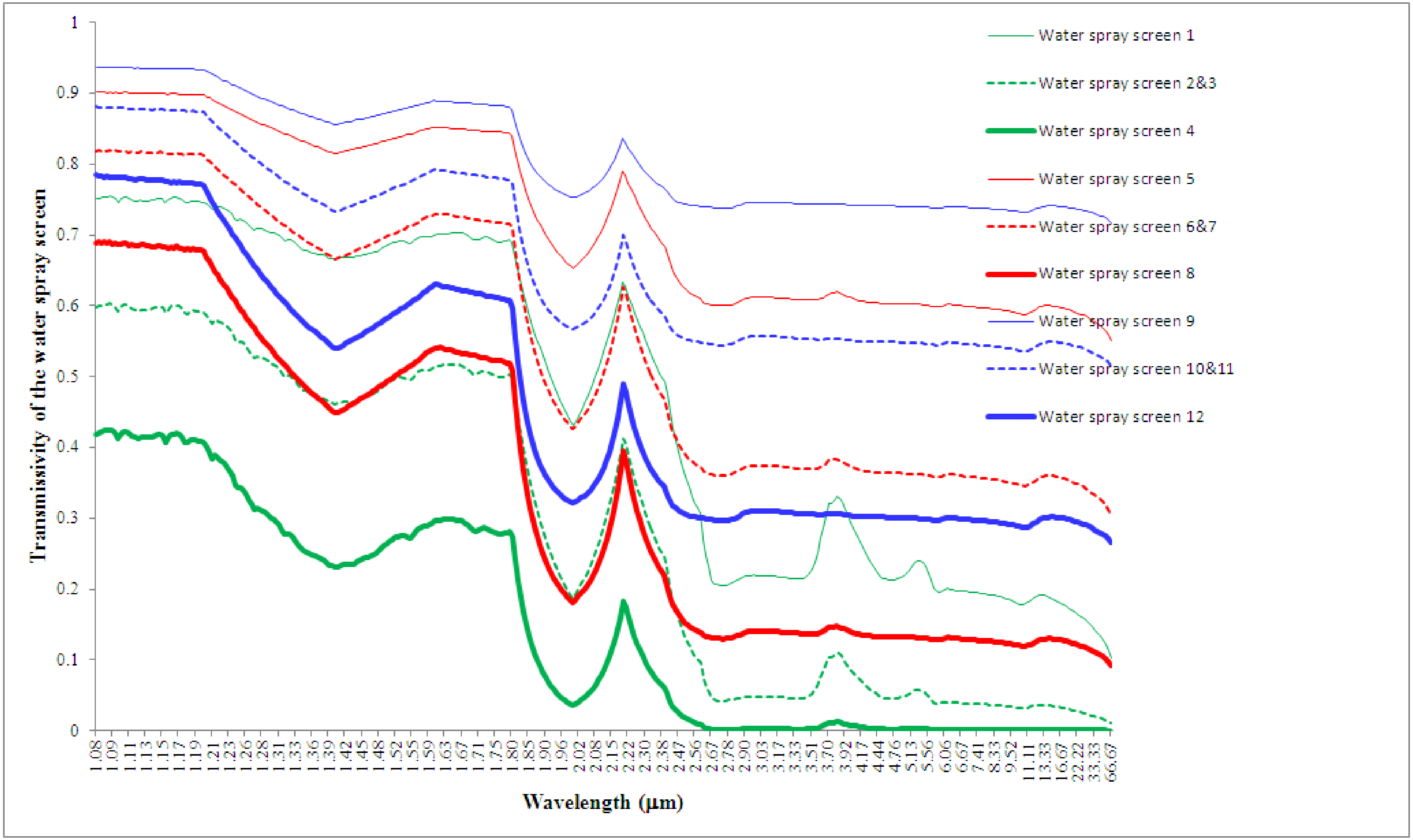
- **Over-prediction of transmissivity with blackbody spectrum compared to actual H_2 flame spectrum**
- **Optical thickness of curtain key parameter in analysing spectra effects**

Analysis of the results



- **Scattering dominant attenuation over absorption (for scenarios studied)**
- **Regions 2 and 4 have a strong influence on attenuation and affect emission bands of H_2O (1.38 µm and 1.87 µm)**

Spectral transmissivities of the curtains



Conclusions

- **A methodology to calculate the spectral and total transmissivities of hydrogen flames presented**

- **Investigation of a wide range of scenarios using the actual H_2 flame emission spectrum shows that water spray curtains could be an effective means to attenuate hydrogen thermal radiation**

- **The blackbody spectrum adopted for hydrocarbon flames simplifies transmissivity calculations (no need to calculate spectral emissivity) but could lead to largely over-predicted transmissivities for hydrogen flames … consequences for designs**

- **For optically thin curtains (optical thickness<0.7) BB spectrum and actual H_2 spectra yield similar total transmissivities**

- **For optically thick curtains (optical thickness>1) BB spectrum should be avoided and the actual H_2 spectra should be used for total transmissivity calculations**

Thank you for your attention!

Questions?