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Analysis of the screening of hydrogen flares and flames thermal radiation with water sprays

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ABSTRACT

Water spray screening is a mitigation technique to reduce thermal radiation from flames to acceptable levels required by safety regulations. The current literature on water screening is limited to hydrocarbon flames. The main goal of the present study is to bridge this knowledge gap by presenting a methodology to predict the water spray screening performance of hydrogen flames using their actual emission spectra. A wide range of hydrogen flames and water screen scenarios are investigated. The results show that although hydrogen flames' emissivities are relatively lower than hydrocarbons', the radiated heat could pose safety risks and water screening is an effective mitigating method. The study further analyses the total transmissivity of water screens calculated from (i) the actual hydrogen spectrum and (ii) a blackbody spectrum. For optically thick spray screens, the blackbody spectrum widely used for hydrocarbon flames screening, could yield unacceptable overestimations of the total transmissivity.

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1. Introduction

Flare systems are important for the safe disposal by combustion of unwanted flammables gases in many hydrocarbon or hydrogen processing plants, and on oil and gas platforms. The design of flare systems must comply with safety regulations to ensure the health and safety of personnel and the integrity of equipment. The amount of radiation heat emitted by flares is important in the design and location of the flare tip on the plant or platform. The permissible heat flux levels, which depend on standards, are typically 1.6 kW/m² for locations where personnel may be continuously exposed (permanent flare), 4.7 kW/m² for areas or exposure of limited duration (several minutes) and 6.3 kW/m² for areas where personnel may have a short time exposure (less than one minute) [1,2]. For the integrity of structures, the permissible design level is 16 kW/m² according to the API 521 [2]. Various

empirical correlations have been developed in the industry to determine the amount of radiant heat flux emitted by flares and received at a given receptor point [2–5]. These correlations are in general based on either the point source model (API-521) or the solid flame model. They require prior knowledge of the amount of energy radiated either as a fraction of the total chemical heat released by the fuel combustion, or the temperature and emissivity of the flame surface in the case of solid flame models, and the geometric view factor between the flame and receiving surface. The simple point source approach is applicable for locations far away from the flame whereas the solid flame model, that treats the flame as a tilted cylinder or frustum of a cone radiating from its surface, provides more accurate results particularly at locations close to the flame [6]. It is worth noting that for flare applications, most of the correlations proposed in the literature for the fractions of heat radiated are based on hydrocarbon fuels with typical

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Nomenclature		Greek symbols	
A_f	flame emission surface area, m^2	$\beta_{d\lambda}$	$=K_{d\lambda} + \sigma_{d\lambda}$, spectral extinction coefficient of droplets, $1/m$
C_d	droplets mass loading or concentration, kg/m^3	$\bar{\gamma}_\nu$	mean half-width of the absorbing lines inside $\Delta\nu$, $1/cm$
d_d	droplet diameter, m	$\bar{\delta}_\nu$	equivalent line spacing, $1/cm$
d_j	jet exit diameter, m	ε	total emissivity of the hydrogen flame
$E_{b\lambda}$	blackbody spectral emissive power, $=\pi I_{b\lambda}$, $W/(m^2 \mu m)$	$\alpha_{f\lambda}$	spectral absorptivity of the hydrogen flame gaseous H_2O
f_s	mass fraction of fuel at stoichiometric conditions	$\varepsilon_{f\lambda}$	spectral emissivity of the hydrogen flame gaseous H_2O
Fr	Froude number	$\bar{\alpha}_{f\lambda}$	spectrally averaged absorptivity of the flame over $\Delta\nu = 25 \text{ cm}^{-1}$
F_v	geometric view factor	$\bar{\varepsilon}_{f\lambda}$	spectrally averaged emissivity of the flame over $\Delta\nu = 25 \text{ cm}^{-1}$
I_λ	spectral radiation intensity, $W/(m^2 \text{ sr } \mu m)$	θ	polar angle between direction of radiation intensity and normal to surface, rad
$I_{b\lambda}$	blackbody spectral radiation intensity, $W/(m^2 \text{ sr } \mu m)$	κ_λ	$=4\pi\tilde{k}_\lambda/\lambda$, spectral absorption coefficient of bulk (film) water, $1/m$
$K_{d\lambda}$	spectral absorption coefficient of water droplets, $1/m$	λ	wavelength of radiation, μm
$\tilde{k}_{f\lambda}$	spectral absorption coefficient of the flame, $1/m$	ν	wavenumber, $1/cm$
\tilde{k}_λ	spectral absorptive index of water	$\Delta\nu$	wavenumber range, $1/cm$
\bar{k}_ν	mean line-intensity to spacing ratio, $1/(atm \text{ cm})$	ρ_e	density of hydrogen jet gas, kg/m^3
L	thickness of the water spray screen, m	ρ_∞	density of ambient gas, kg/m^3
L_f	flame length, m	ρ_d	density of water droplets, kg/m^3
L_m	flame mean beam length, m	σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$
\tilde{m}_λ	spectral complex refractive index of water, $\tilde{m}_\lambda = \tilde{n}_\lambda - i\tilde{k}_\lambda$	τ_{ws}	total transmissivity of the water spray screen
N_d	number of droplets per unit volume, $1/m^3$	$\tau_{ws,\lambda}$	spectral transmissivity of the water spray screen
\tilde{n}_λ	spectral index of refraction of water	τ_{bb}	total transmissivity of the water spray screen for a blackbody incident radiation
P	gas total pressure, 1 atm	$\bar{\tau}_{f\lambda}$	spectrally averaged transmissivity of the flame gaseous H_2O over $\Delta\nu = 25 \text{ cm}^{-1}$
p_0	hydrogen release pressure, MN/m^2	ψ_λ	spectral atmospheric transmissivity between flame and water screen
Q	efficiency factor of water droplets (Q_{abs} absorption, Q_{sca} scattering, Q_{ext} extinction)	ϕ	azimuthal angle, rad
q_{inc}	total radiation heat flux incident on water screen, W/m^2	χ	molar fraction
$q_{inc,\lambda}$	spectral radiation heat flux incident on water screen, $W/(m^2 \mu m)$	$\omega_{d\lambda}$	spectral albedo of droplets
q_{tr}	total radiation heat flux transmitted through the water screen, W/m^2	$\sigma_{d\lambda}$	spectral scattering coefficient of droplets, $1/m$
$q_{tr,\lambda}$	spectral radiation heat flux transmitted through the water screen, $W/(m^2 \mu m)$	Ω	solid angle or radiation angular direction, steradian
T_f	flame temperature or gaseous H_2O temperature, K		
t_λ	spectral optical depth or optical thickness of the water spray screen		
V_f	flame volume, m^3		
x	distance, m		
W_f	flame width, m		
		Abbreviations	
		SNB	Statistical Narrow Band gas radiation model

values of 0.2 for methane, 0.33 for propane and 0.4 for other hydrocarbon fuels [5].

The venting and flaring of hydrogen, which could occur on offshore and onshore process plants or on hydrogen refuelling and energy stations, must also comply with safety requirements. Although the flow rate at which hydrogen may be vented or flared depends on specific conditions, it is usually accepted that smaller flow rates of hydrogen 0.001–0.002 kg/s may be vented directly into the atmosphere without flaring. Larger hydrogen flow rates of 0.1–0.2 kg/s should be disposed of by flaring [6,7]. The flaring process consists of the ignition and combustion of the hydrogen fuel, typically resulting in hydrogen jet diffusion flames. The study of hydrogen jet

flames has received considerable attention in recent years, with various correlations proposed in the literature for the jet flame length, width, stability and fraction of (combustion) heat radiated [8–11]. This renewed interest in hydrogen research is mainly due to its environmental benefits (reduced pollution) and the projected limited availability of fossil fuels. For hydrocarbon fuels where soot radiation is significant, the flame length definition is based on the visible flame length. In contrast, hydrogen flames are often barely visible in daylight and gaseous emission by H_2O accounts for nearly all radiant emission [10,11]. The fraction of heat radiated for hydrogen jet flames strongly depends on the jet exit diameter and flow rates; fraction values of up to 0.16 are reported in the literature

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