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Contribution to Fire Protection of the LNG Storage Tank Using Water Curtain

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Abstract

In the early years of the oil and gas industry, fire in storage tanks was the common root of most of the incidents. One technique to protect the integrity of neighboring tanks is the water spray curtain, which can provide thermal shielding against fire. This study presents a numerical simulation of radiative heat transfer by the Mont Carlo method through a semitransparent medium (water spray curtain) containing water droplets and gas for the design of an effective thermal shielding system to protect LNG (or combustibles) storage tank from fire. This model will allow us to calculate exactly the attenuation factor of the water curtain as a function of its thickness, density and the size of water droplets. The medium is considered as a non grey, absorbing and anisotropically scattering. The spectral behavior of the medium is taken into account by the Mie theory and the SNB model applied respectively to water droplets and gas (H_2O, CO and CO_2). The calculated results are satisfactorily in agreement with the experimental data.

Keywords: *Radiative heat transfer, Water curtain, Mie scattering, SNB model, Monte Carlo method, LNG storage tank.*

1. Introduction

The modeling of the radiation heat transfer in participating mediums plays an important role in many technological applications such as the monitoring in real-time of manufacturing processes of materials by infra-red imagery, the medical imagery, the treatment of materials and fire protection by water spray curtains, of industrial facilities at risks (in particular in petrochemical and oil and gas industries). The fires which have occurred in these sites showed that the radiation emitted by the fire flames could involve series of new fires because of heat propagation per radiation. To protect the other targets from fires, water shields called water curtains were designed and used as safety devices against the fires, in various configurations. These devices use water spray made up of very fine particles of water dispersed in air, form a shield limiting the propagation of the flames radiation. Figure 1 schematizes an example of fire safety device using a ramp, which represents an association of several nozzles, all fed in series. The efficiency of such device lies first in the absorption of fire radiation by the wet air (CO, CO_2 and H_2O) and then in the absorption and the scattering of radiation by water droplets.

2. Formulation of the Problem

Let us consider a target receiving a strong radiative heat from fire sector (Fig. 1), simulated as a collimated source due to a blackbody at high temperature. The water curtain would behave as a thermal shielding in order to attenuate the incoming radiation. We assume that the curtain will be located in front of the target to be protected, but sufficiently far from fire to avoid any interaction with the flames, so that the statistical distribution of the droplets remains a realistic description of the real spray.

2.1. Assumptions and Limitations

In this study, we consider the following assumptions [1]:

- Temperature and relative moisture in the medium are constant and set to 300K and 60% respectively
- Gas and droplets are assumed to have the same temperature,
- All volume fractions (for the droplets and the gaseous species) are supposed to remain constant,
- All participating species are assumed to act independently, so that global radiative properties may be obtained by a simple addition of their respective contributions.

2.2. Modeling of Medium Radiative Properties

As we mentioned before, the water curtain is a participating medium composed from two phases: a liquid phase made up from droplets injected in air, and a gaseous phase composed from water vapor, carbon monoxide and carbon dioxide. Therefore, the knowledge of the medium's radiative properties (Absorption coefficient, the scattering coefficient, and the scattering phase function) is needed in order to evaluate the radiation heat transfer through the studied medium.
In this study, the radiative properties of the droplets are calculated applying the Mie theory. The model SNB (statistical narrow band model) is used to calculate directly the transmissivities of the gaseous phase thus a reduction in the computed time.

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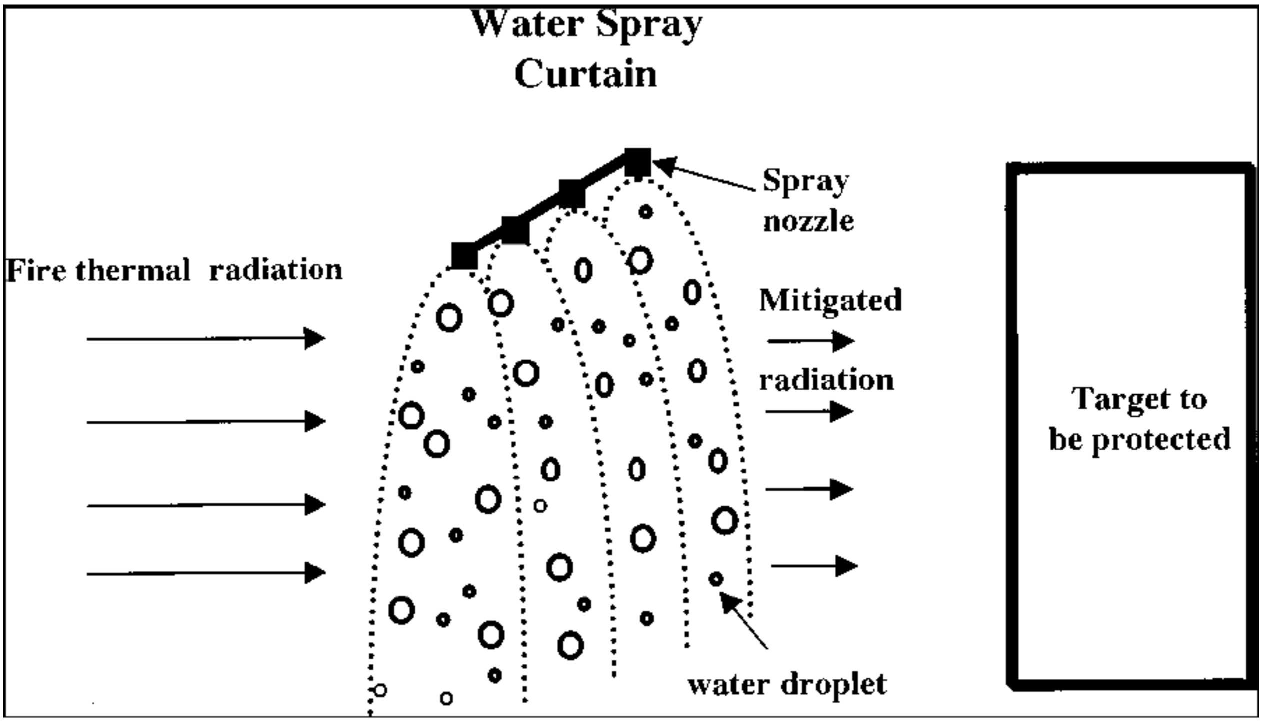

Fig. 1. Water Curtain for Fire protection [4]

2.2.1. Computing Radiative Properties of Droplets by Mie Theory

The theory of Mie is based on the integration of the equations of electromagnetism of Maxwell inside and outside a particle. The solution of these equations allows determining the scattering coefficients of Mie a_n and b_n which are obtained by the following expressions:

$$a_n = \frac{m\Psi_n(mX)\Psi'_n(X) - \Psi_n(X)\Psi'_n(mX)}{m\Psi_n(mX)\zeta_n(X) - \Psi_n(X)\zeta'_n(mX)}$$
$$b_n = \frac{\Psi_n(mX)\Psi'_n(X) - m\Psi_n(X)\Psi'_n(mX)}{m\Psi_n(mX)\zeta_n(X) - m\zeta_n(X)\Psi'_n(mX)} \tag{1}$$

m is the complex refraction index of water (m=n-ik, with i^2=1),

Another form to calculate the scattering coefficients of Mie a_n and b_n was presented by Bohren and Huffman [2]. This form is simpler for the programming and numerically more stable:

$$a_n(X,m) = \frac{\left(\frac{D_n(X,m)}{m} + \frac{n}{X}\right)\psi_n(X) - \psi_{n-1}(X)}{\left(\frac{D_n(X,m)}{m} + \frac{n}{X}\right)\zeta_n(X) - \zeta_{n-1}(X)} \quad n \ge 1$$
$$b_n(X,m) = \frac{\left(mD_n(X,m) + \frac{n}{X}\right)\psi_n(X) - \psi_{n-1}(X)}{\left(mD_n(X,m) + \frac{n}{X}\right)\zeta_n(X) - \zeta_{n-1}(X)} \quad n \ge 1 \tag{2}$$

Finally, the properties of individual particles (absorption, extinction and scattering efficiencies and the scattering phase function) for a given droplet size are defined by the following equations:

$$Q_{s,\lambda}(d) = \frac{2}{X^2}\sum_{n=1}^{N_{max}}(2n+1)\left(|a_n|^2 + |b_n|^2\right)$$
$$Q_{e,\lambda}(d) = \frac{2}{X^2}\sum_{n=1}^{N_{max}}(2n+1)\Re\left(a_n + b_n\right) \tag{3}$$
$$Q_{a,\lambda}(d) = Q_{e,\lambda}(d) - Q_{d,\lambda}(d)$$

The number of summations is obtained by the following truncation criterion [2]:

$$N_{max} = \max(X + 4X^{1/4} + 2, |m.X|)$$

The scattering phase function of Mie for a spherical particle is function of the wavelength, the diameter of the particle and the scattering angle θ [2]:

$$\Phi_\lambda^{Mie}(a,\theta) = 2\frac{|S_1(\theta)|^2 + |S_2(\theta)|^2}{X^2\,Q_d(a)} \tag{4}$$

Where S_1 and S_2 are the complex amplitude functions which can be obtained thanks to the coefficients of Mie (a_n and b_n).

$$S_1(\theta) = \sum_{n=1}^{N_{max}}\frac{2n+1}{n(n+1)}\left[a_n\pi_n(\mu) + b_n\tau_n(\mu)\right] \tag{5}$$

$$S_2(\theta) = \sum_{n=1}^{N_{max}}\frac{2n+1}{n(n+1)}\left[b_n\pi_n(\mu) + b_n\tau_n(\mu)\right] \tag{6}$$

To model the global radiative properties of polydispersion, we assume that all participating species act independently. So that global radiative properties may be obtained by a simple addition of their respective contributions of the various classes of diameters [3]:

The spectral coefficient of absorption noted k_λ . Its expression is given by:

$$k_\lambda = \sum_{i=1}^{N_c} \pi \frac{d_i^2}{4} N_i Q_a(d_i) \tag{7}$$

The spectral coefficient of diffusion noted σ_λ . Its expression is given by:

$$\sigma_\lambda = \sum_{i=1}^{N_c} \pi \frac{d_i^2}{4} N_i Q_d(d_i) \tag{8}$$

The spectral coefficient of extinction noted β_λ . Its expression is given by:

$$\beta_\lambda = \sum_{i=1}^{N_c} \pi \frac{d_i^2}{4} N_i Q_e(d_i) \tag{9}$$

The scattering phase function of Mie is given by the following expression:

$$\Phi_\lambda^{Mie}(\theta) = \frac{1}{\sigma_\lambda} \sum_{i=1}^{N_c} \pi \frac{d_i^2}{4} Q_s(d_i) \Phi_\lambda^{Mie}(d_i, \theta) N_i \tag{10}$$

N_c is the number of classes of droplets diameters.

N_i is the number of particles per unit of volume of diameter d_i

In order to reduce the computation time, the first way is to approximate the polydispersion by a monodispersion of droplets characterized by a Sauter Mean diameter D_{32} and concentration C, the extinction coefficient β is given by:

$$\beta = \frac{3 Q_e C}{2 \rho d}$$

Where: Qe is the extinction efficiency factor obtained by the Mie theory, ρ water density, d Sauter Mean Diameter and C the concentration.

The second way is to approximate the scattering phase function of Mie, in fact, this function is complex and difficult to use in term of calculating time, and this is why we prefer to use simpler functions of phase, containing few parameters to be identified. In what follows, the model of Henyey and Greenstein is used. This model depends on one parameter g (factor of asymmetry) and given by the following expression:

$$\Phi(\theta, g) = \frac{1 - g^2}{\left[1 + g^2 - 2g\cos(\theta)\right]^{3/2}} \tag{11}$$

With g equal to [4]:

$$g = \frac{4}{x^2 Q_s} \sum_{n=1}^{\infty} \left[\frac{n(n+2)}{n+1} \Re\left[a_n \bar{a}_{n+1} + b_n \bar{b}_{n+1}\right] + \frac{2n+1}{n(n+1)} \Re\left[a_n \bar{b}_n\right] \right]$$

The representation of the factor of asymmetry g in a diagram wavelength-diameter (Fig. 2) shows that the factor g can be approximated with a value of g=0.8 for a Mean Sauter diameter of droplets (D_{32}) around 100µm in the range of the wave length [1.55; 12.5] µm.

2.2.2. Modeling Gas Radiative Properties by the Statistical Narrow Bands Model (SNB)

In this study, we have made the choice to use the SNB model in order to calculate directly the average transmissivity for a given wavelength. The expression of the average transmissivity over a narrow bandwidth Δλ for a medium thickness Δs (in cm), containing a homogeneous and isothermal gas at a total pressure P_r (in atm) is:

$$T_{r\lambda} = \exp\left[-2 \frac{\gamma}{\bar{\delta}} \left(\sqrt{1 + xplk \frac{\bar{\delta}}{\gamma}} - 1 \right) \right] \tag{12}$$

In this expression γ(in cm-1), $\bar{\delta}^{-1}$ (in cm) and K (in cm-1 atm-1) corresponds respectively to the average width of the lines, average spacing between two lines and the average absorption coefficient. These spectroscopic data are provided by Soufiani and Taine [5].

3. Resolution

The resolution of the Radiative Transfer is done by the Monte Carlo method. The studied medium is a participating medium, no gray, isothermal, absorbent and diffusing in an anisotropic way placed between two black areas of infinite size. The assumption of unidimensionnality is adopted. The studied configuration is described on figure 1. The objective is to calculate the ratio between the flux crossed P2 and the flux emitted by P1.

The radiative model established consists in calculating in the first time the average spectral transmissivity of gas (H2O, CO2 and CO) by SNB model, after a simulation of Monte Carlo is carried out to calculate the spectral transmissivity of the droplets.

The average spectral transmissivity of the medium is calculated as the product of average spectral transmissivity of gas and the droplets.

$$T_{Curtain,\lambda} = T_{Droplets,\lambda} * T_{Gas,\lambda} \tag{13}$$

3.1. Validation of the Radiative Model

In order to validate our radiative model, we followed the same steps as in the reference [1]. A first validation was carried out, testing the ability of the current code to simulate the transmissivity of a spray as a function of the wavelength. Comparisons have been carried out with the experimental data by Dembélé [4]. The numerical conditions are the following: the spray is referred as TG03-1bar, with droplets diameter varying between 15 and 170 µm, with a calculated Sauter Mean Diameter (D_{32}) of 100.4 µm and droplets concentration of 8.28x10-6 m3 of droplets/m3 of air, the temperature and moisture inside the spray are 300K and 60% respectively. The volume fractions for H_2O and CO_2 were fixed at 2.11x10-2 and 2.93x10-4 m^3 of gas/m^3 of air respectively. The width of the spray is 0.24m.

The results are presented in the spectral range of [1.5 to 12.5 µm] corresponding to the corresponding to the main part of the incoming radiation, where the experimental results are available to allow a comparison. Figure 2 presents a comparison between the experimental data of Dembélé [4], and our radiative model with a spectral discretization of 367 bands. Absorption Peaks due to H_2O (at 2.7 µm and around 6.5 µm) and to CO_2 (at 4.3 µm) are reproduced. We can observe small local anomalies in the maximum intensities but the result remains very satisfactory. An averaged transmissivity of 91.74% was obtained numerically, integrating the spectral results between 1.5 and 12.5 µm, whereas a value of 92.04% was quoted in the experimental study. These results are very satisfactory by taking into account possible uncertainties, due for example, to the exact distribution of droplets or the reproduction of the experimental data.

A second validation was carried out under similar conditions but with a second spray referred as TG03-3bar, droplets diameter varying between 20 and 250 µm, with a calculated Sauter Mean Diameter (D_{32}) of 101.2 µm and droplets concentration of 24.4x10-6m3 of droplets/m^3 of air. The volume fractions for H_2O and CO_2 were fixed at 2.11x10-2 and 2.93x10-4 m3 of gas/m3 of air respectively. The results are represented on figure 3. One can notice that the experimental data are well reproduced by the numerical simulation.

As can be seen, here again the results is satisfactory. We highlight that the increase in pressure provides smaller droplets with a higher global concentration. Smaller droplets are known to enhance the scattering ability of the spray, with a decrease of the forward scattering peak. In addition, the increase in the concentration also enforces the radiation extinction. An averaged transmissivity of 82.42% was obtained numerically, integrating the spectral results between 1.5 and 12.5 µm, whereas a value of 82.72% was quoted in the experimental study.

The two previous tests show that our radiative model can be used as a 1D model of reference, which makes it possible to predict exactly the same characteristics of spray transmissivity under other test conditions.

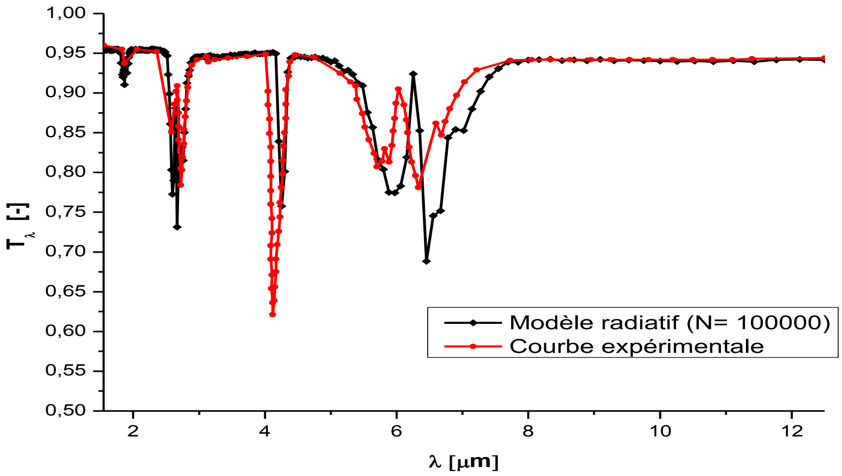

Fig. 2. Predicted spectral transmissivity for the "TG03-1 bar" case and comparison with the experimental data by Dembélé [4]

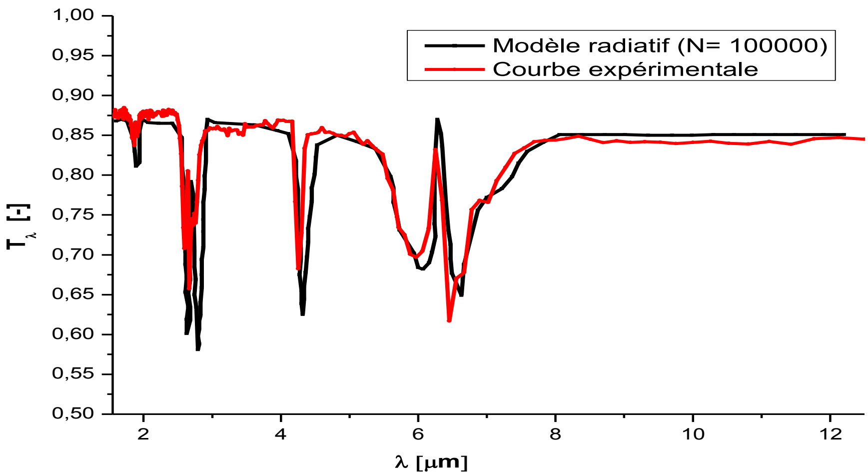

Fig. 3. Predicted spectral transmissivity for the "TG03-3 bar" case and comparison with the experimental data by Dembélé [4]

4. Results

4.1 Characterization of Real Distribution

The results presented on figures 4 and 5 prove that the use of D_{32} to characterize the real distribution gives very good performances, at the time when the other median values are less satisfactory. The error between the real distribution and those obtained by using D_{32} is equal to 0.04% in the case of TG03-1bar and 0.17% in the case of TG03-3 bar. By comparison, the error induced with the use of D_{10} under the same conditions was larger of 1.88% and 7.55%, respectively. The saving of time of calculation with D_{32} can be really important, since the radiative properties based on the theory of Mie must be calculated once, instead of once for each class of size. In spite of that, exactitude in the forecast of the transmissivity remains satisfactory.

4.2. Water Spray Curtain Characterization

4.2.1. Influence of Droplets Size

A water curtain is in practice formed by a series of nozzles arranged on a ramp. The curves of transmissivities represented on figure 6 highlight the results obtained by the calculation of the effectiveness of the drops using the theory of Mie. The study of these curves shows that the attenuation of the radiation by scattering (fine droplets, d=10μm) is more important than by absorption (large droplets, d=200μm).

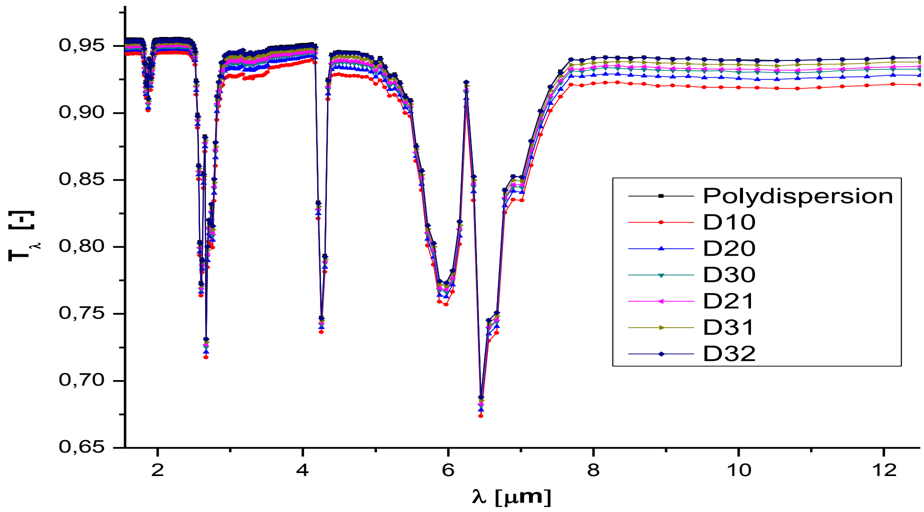

Fig. 4. Spectral transmissivities predicted for monodispersions based on various mean diameter, comparison with the real polydispersion result ("TG03-1 bar" case)

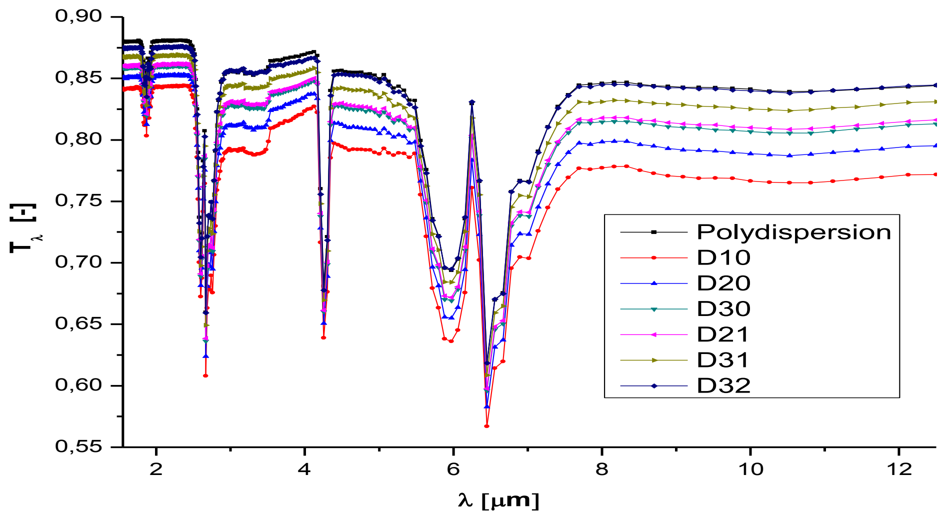

Fig. 5. Spectral transmissivities predicted for monodispersions based on various mean diameter, comparison with the real polydispersion result ("TG03-3 bar" case)

4.2.2. Influence of Droplets Concentration (nozzle density)

A second way to improve the attenuation of radiation is to increase the concentration of droplet by increasing sprays density. Simulations realized on the case TG03-1bar is presented on figure 7. This figure represent curve of transmissivities for various densities of sprays on one ramp; it corresponds to a density of 4.2, 8.3, 16.6 and 33.3 sprays per meter. It is possible to note that the average transmissivities decreases with the density of sprays, which increases the effectiveness of the water curtain.

4.2.3. Influence spray width (curtain thickness)

The third way to improve the attenuation of radiation is to increase the thickness of curtain. Simulations realized on the case TG03-1bar is presented on figure 8. This figure represent curves of transmissivities for various densities of ramps 1, 2, 3 and 4 ramps corresponds to thicknesses of 0.24, 0.48, 0.72 and 0.96m respectively. It is possible to note that the average transmittance decreases with the density of ramps, which increases the effectiveness of our water curtain.

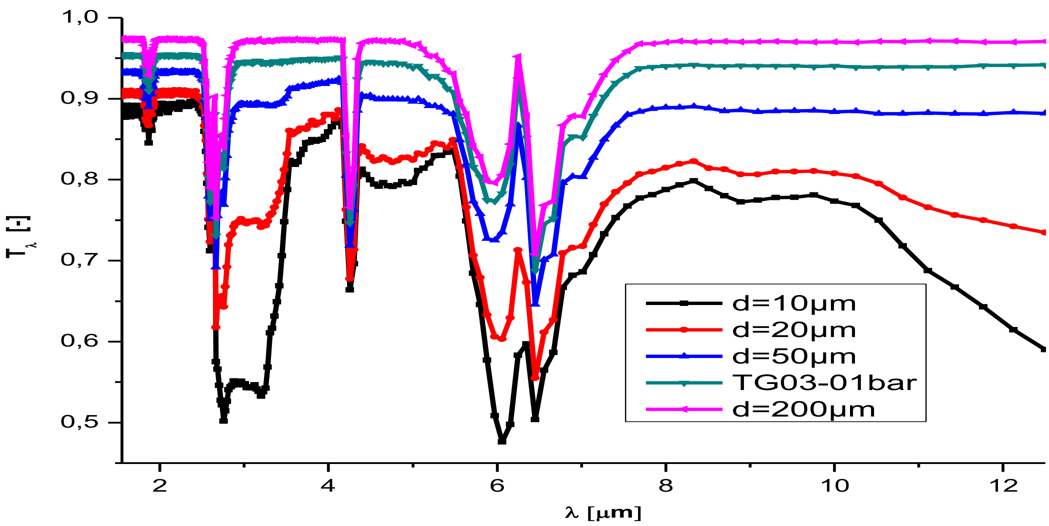

Fig. 6. Spectral Transmissivities with Influence of droplets size

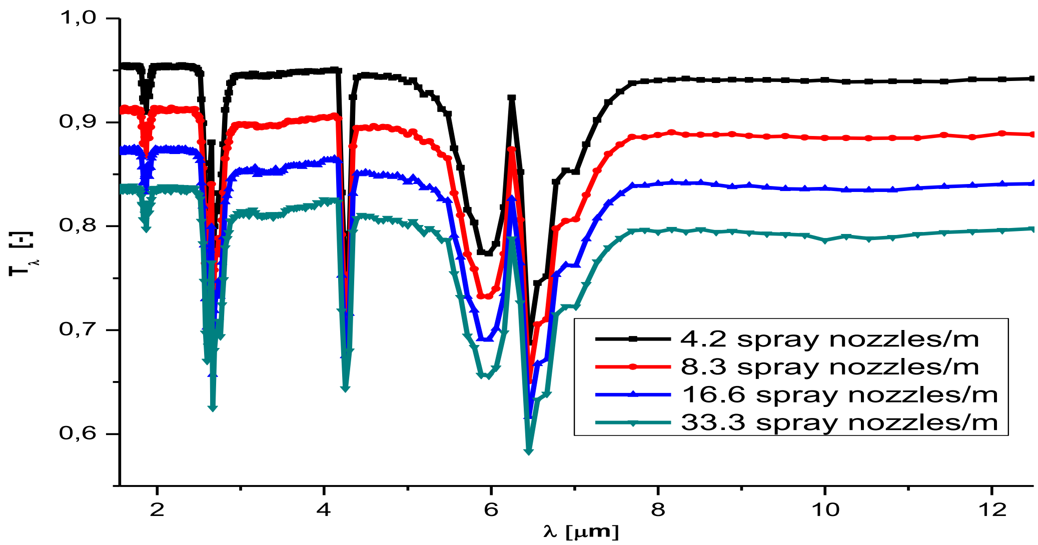

Fig. 7. Spectral transmissivities with Influence of nozzle density

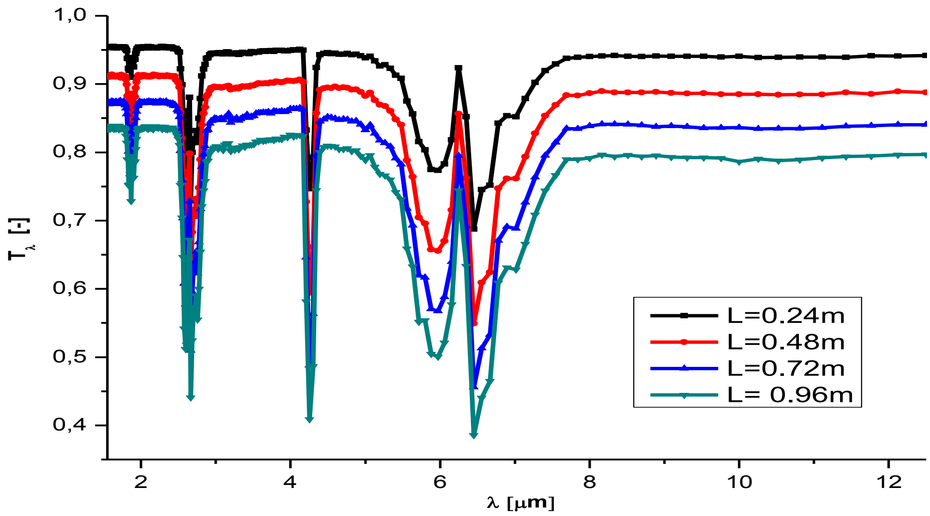

Fig. 8. Spectral transmissivities with influence of ramp density.

5. Determination of a Correlation Applicable to the Water Curtain

This correlation makes it possible to precisely calculate average transmittance through a water curtain thickness X (m) with a Sauter Mean diameter d (D_{32}) in (µm) and a concentration C:

$$T_{r,moy} = A + B \cdot EXP(-K \cdot x) \quad (14)$$

Where: A, B, K: constants

$$A = A_1 + B_1 \cdot EXP(-K_1 \cdot C)$$

$$B = A_2 + B_2 \cdot C + C_2 \cdot C^2 + D_2 \cdot C^3$$

$$K = A_3 + B_3 \cdot C$$

Coefficients A:

$$A_1 = 5{,}9153 \cdot 10^{-7} \cdot d^{1.93724}$$

$$B_1 = 0{,}05049 + 0{,}00097 \cdot d + 0.00001 \cdot d^2 - 3{,}6678 \cdot 10^{-8} \cdot d^3$$

$$K_1 = 280070{,}36363 + 440742{,}10224 \times 0{,}99482^d$$

Coefficients B:

$$A_2 = 0.93004 + 0.00046d - 0.00002d^2 + 5.8404.10^{-8} d^3$$

$$B_2 = 151123{,}57233 - 242740{,}56842 \cdot 0{,}99086^d$$

$$C_2 = -29886137732{,}83847 - 32430741670{,}51099 \cdot 0{,}99603^d$$

$$D_2 = 6{,}6059 \cdot 10^{13} + 347500970849{,}22516 \cdot d + 38594612241{,}03359 \cdot d^2 - 127139411{,}8307 \cdot d^3$$

Coefficients K:

$$A_3 = 0{,}22321 + 1{,}60198 \cdot EXP(-0{,}04811 \cdot d)$$

$$B_3 = 3811{,}14231 + 54288{,}6454 \times EXP(-0{,}0106 \times d)$$

This correlation is valid for the assumptions imposed on the beginning of work; In order to make this correlation more practical (to carry out water curtains with conduits of the type TG03), following simplifications are introduced according to the number of slopes N and the sprays nozzles (tubes) m to place to reach a given level of attenuation:

$$T_{r,moy} = A + B \cdot EXP(-0{,}24 \cdot K \cdot n) \quad (15)$$

With: N is the number of ramps; (n=1,2,3 ....)
m is the number of spray nozzles/m; (m=1,2,3 ....)

$$A = A_1 + B_1 \cdot EXP(-K_1 \cdot C_m)$$

$$B = A_2 + B_2 \cdot C_m + C_2 \cdot C_m{}^2 + D_2 \cdot C_m{}^3$$

$$K = A_3 + B_3 \cdot C_m$$

$$C_m = m \cdot C$$

6. Design of Water Spray Curtain for LNG Storage Tanks Protection

Now, the previous theoretical study will enable us to deal with real problem involved in the design of a water curtain for the protection of the LNG storage tank against fires. The study carried out by Buchlin [6] shows the applicability of the water curtains as a safety device of the storage tank. In this part of study, the following scenario is considered. A storage tank, 20 m high and having an outer diameter of 20m, receives a radiant heat flux of 40 kW/m^2 from a fire at 1300K.

The simulation points out that before 4m and beyond 8 m of travelling distance, the curtain does not exhibit sufficient attenuation capability as displayed in figure 13. According to such a finding, the following design can be projected. It involves 3 circular ramps. The first ramp is positioned 2 m above the top of the tank while the second and third ramp at vertical interval of 7m below.

To protect the integrity of the storage tank, the heat flux received by the side surface of the tank must be reduced to a minimum value lesser than 3 kW/m ² corresponding to the zone of the significant dangers to the human life. The temperature and relative moisture in the medium are constant and set to 300K and 60% respectively.

The Simulation carried out by Buchlin [6] on a water curtain placed on a height of 10m shows that before 4m and beyond 8 m of travelling distance, the curtain does not exhibit sufficient attenuation capability as displayed in figure 3. According to such a finding, the following design can be projected. It involves 3 stages of circular ramps. The first stage of ramps is positioned 2 m above the top of the tank while the second and third stage at vertical interval of 7m below. This study showed that the curtain retains its hydrodynamic integrity over the 7m distance for wind speed not exceeding 4m/s.

In order to design this water curtain, we used the correlation (15). The simulation results can be shown in Table 1 below.

7. Conclusion

In this study, a 1D treatment of the radiative transfer inside a water spray curtain, irradiated with a high temperature source, has been tested and validated. The numerical simulation performed with the 1D model shows that the total radiative attenuation afforded by the water spray curtain can equal up to 90% can be expected, thus, the water spray curtain to protect storage tank from fire radiation can be an efficient thermal shielding technique.

Table 1. Simulation of GNL storage tank protection

Type of Nozzle	Number of ramp on each stage	Number of spray nozzles on each ramp		Total Number of spray nozzles	heat flux on the surface of the tank (attenuated flux kW/m^2)	Attenuation factor (%)
TG03-1bar	08	Rampe 1	599	9804	2.8	91.56
		Rampe 2	587			
		Rampe 3	575			
		Rampe 4	563			
		Rampe 5	551			
		Rampe 6	539			
		Rampe 7	527			
		Rampe 8	514			

Nomenclature

d	Diameter of the particule, m
g	Asymmetry factor
m	Complex index of refraction of water
n	Refractive index
Q_a	Absorption efficiency factor
Q_d	Scattering efficiency factor
Q_e	Extinction efficiency factor
X	Particle size parameter
$\Re$	Real part of complex number

Greek Symbols

Ψ_n, ξ_n Riccati-Bessel functions

Subscripts

a	Absorption
d	Scattering
e	Extinction
λ	at a given wavelength

Acknowledgments

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References

[1] Boulet P, Collin A, et Parent G. Heat transfer through a water spray curtain under the effect of a strong radiative source. Fire Safety J. 2006; 41(1), 15–30. http.dx.doi.org/10.1016/j.firesaf.2005.07.007

[2] Bohren CF, Huffman DR. Absorption and scattering of light by small particles. New York: Wiley, 1983.

[3] Collin A. Transferts de chaleur couplés rayonnement - conduction – convection Application `a des rideaux d'eau soumis `a une intense source radiative. Thèse de Doctorat, Université HENRI POINCARE -Nancy I, France, 2006.

[4] Dembélé S. Modélisation et étude expérimentale des transferts de chaleur par rayonnement dans un rideau d'eau diphasique. Application à la protection incendie d'installations industrielles à risques. Thèse de Doctorat, Institut National des Sciences Appliquées de Lyon, France, 1998.

[5] Soufiani A, and Taine J. High temperature gas radiative property parameters of statistical narrow-band model for H2O, CO2 and CO, and correlated-K model for H2O and CO2. Technical note in International Journal of Heat and Mass Transfer 1997; 40 :987–991.

[6] Buchlin JM. Water sprays as mitigation means. Invited paper in international workshop on multiphase and complex flow simulation for industry: Physical, mathematical, numerical models and software for safety and design improvements, Carge `se, Corsica; 2003.