Thermal Shielding by Water Spray Curtains

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Abstract
The mitigation of the consequences of storage-tank fire is a great safety concern in petro-chemical and gas industries. A technique to protect the integrity of neighbouring structures is the water spray curtain. It can be operating downward in front of or oriented to the surface to be shielded. Simple modelling, laboratory experiments and field tests for these two types of thermal shielding are presented.

Attenuation factor of 50% to 75% can be expected with the vertical curtain while 90% can be reached with the impinging curtain if spray overlapping is achieved.

1. Introduction
Nowadays, the water spray curtain is recognised as a useful technique to mitigate major industrial hazards. It combines attractive features such as simplicity, efficacy and adaptability to different types of risk [Buchlin (2003)]. In case of reservoir fire, water sprays can provide thermal shielding to maintain the integrity of neighbouring structures [Lev (1989), Strachan and Lev (1989). Nedelka, Bauer and Copalle (1992)]. The curtain composed of water droplets behaves as a filter [Thomas, (1952), Lenoir and Sanders (1972)] and can afford significant reduction of the incident
radiation that impinges on sensitive surfaces such as petro-chemical or LNG storage tanks.

The water curtain may be located vertically downward in front the surface to be protected as sketched in figure 1a. This sort of shielding (the vertical spray curtain) has been thoroughly investigated at the von Karman Institute in the frame of the common European project ASTRRE coordinated by Lieto (1997) and carried out in close collaboration with the University Claude Bernard and the Centre de Thermique de l'INSA (CETHIL) from Lyon (France), in the frame of the European program Environment [Griolet, Lieto, Dembele, Delmas, Raynaud, Sacadura et al (1998)].

The water curtain may also be oriented towards the tank to form a continuous fog casing protecting all the tank wall as sketched in figure 1b. Potential improvement of the thermal shielding by impacting directly the water (the impinging spray curtain) on the structure is anticipated because the thermal shielding is now due to both the impinging droplet phase and the resulting water falling film [Hald and Buchlin (2003)].

The paper describes and illustrates the main achievements of studies conducted for this type of hazard mitigation and to which the VKI participated. The methodology adopted is threefold: model development, laboratory experiments in a small-scale facility and field-tests with real products.

2. The spray curtain

As shown in figure 1, the water curtain may be formed by one or several spray booms separated by a horizontal distance $E_h$ and/or a vertical distance $E_v$. Each spray line is equipped with $N_n$ pressure nozzles, generally equally spaced.
The sprays are formed by pressurized nozzles, often of full cone type, characterised by the flow number, $F_N$, which is the ratio of the nozzle flow rate to the square root of the operating relative pressure, $\Delta P$. Then, the flow rate per unit of curtain length is:

$$m_{i,m} = n_n F_N \sqrt{\Delta P}$$

(1)

Where $n_n$ is the nozzle density (#/m).

The spray is a polydispersed two-phase flow characterised by a droplet size distribution. This latter may be readily modelled by a histogram expressed in terms of number of droplets $n(d_i)$ per class – diameter $d_i$. Measurements performed with Laser Phase Doppler anemometry conducted in the VKI Water-Spray facility Laboratory shows that the droplet size distribution in water sprays produced by pressurised nozzles can be modelled by the Rosin-Rammler relation and that the Sauter mean diameter, $SMD$, can be expressed in function of $\Delta P$ and the nozzle diameter $D_o$ [St Georges and Buchlin (1994)}]:

$$SMD = \frac{\sum_{i=1}^{N_d} d_i^3 \cdot n(d_i)}{\sum_{i=1}^{N_d} d_i^2 \cdot n(d_i)} = C_o \frac{D_o^3}{\Delta P^3}$$

(2)

$N_d$ is the total number of droplet classes used to represent the size distribution. $C_o$ is a constant of the order of 1, the exact value of which depends on the nozzle design.

Generally, in a water curtain the sprays interfere each with other so that after some distance from the nozzle, it constitutes a dense fence. The gas low within the curtain is made of air entrained by momentum exchange with the surrounding environment, and of an excess of water vapour resulting from droplet evaporation.
3. Theoretical Modelling

3.1 Vertical spray curtain

The physical modeling of the thermohydraulic behaviour of liquid sprays including phase change and radiative heat transfer has already been reported and described in details by the author [Buchlin (1992), (1995) and (2003)]. Among the proposed approaches, a simple one-dimensional model has been implemented in an engineering code.

The mass balance expresses that the gas (subscript $g$) flow rate inside the spray varies according to the external gas entrainment (subscript $g,ent$) provoked by the momentum exchange between the two phases, and the liquid droplet (subscript $di$) evaporation:

\[ \nabla m_g = \nabla m_{g,ent} - \sum_{i}^{nc} \nabla m_{di} \quad (3) \]

The momentum change of the two-phase flow is due to the presence of the body force modeled by the apparent weight of the particulate phase:

\[ \nabla (u_g m_g) + \sum_{i}^{nc} \nabla (u_{di} m_{di}) = \sum F_{vol} \quad (4) \]

The enthalpy change of the two-phase flow is the result of the input from the external gas entrainment and of the thermal radiation (subscript $r$) absorbed by the gas phase (water vapor content) and by the droplets:

\[ \nabla (m_g h_{eg}) + \sum_{i}^{nc} \nabla (m_{di} h_{e_{di}}) = \sum_{i}^{nc} \dot{Q}_{r,di} + \dot{Q}_{r,g} + \nabla (m_{g,ent} h_{e_{g,ent}}) \quad (5) \]

A lagrangian approach is adopted to describe the droplet phase. The momentum, heat and mass transfer can be expressed by the same generic equation applied to each droplet class $i$: 
\[
\frac{d\Theta_i}{dt} = \frac{\Delta \Theta_i}{\tau_i} + S_i
\]  

(6)

where \( \Theta_i \) is the velocity, the temperature and the mass of the droplet \( i \), respectively and \( \tau_i \) the relaxation time of the transport to be considered; this characteristic time is a strong function of the droplet Reynolds number through the drag coefficient (momentum), the Nusselt number (heat transfer) and the Sherwood number (mass transfer). Appropriate correlations are used to determine these dimensionless numbers. \( S_i \) represents the source term; it is the buoyancy force in the momentum equation, and the latent heat of vaporization and the radiation in the thermal equation.

The radiative transfer consists of a set of interactions between the radiative spectral intensity and the polydispersed medium. The droplets, forming a discrete phase, absorb and scatter the incident radiation. Moreover, due to its internal energy, the droplet also reemits thermal radiation. The gas phase, considered as a continuous medium, also absorbs and emits thermal radiation. These different mechanisms lead to the attenuation of the radiative flux going through the spray and to an increase of the two-phase enthalpy.

Since the radiative behavior of the liquid and gas phases differs according to the wavelength of the incident energy, a spectral treatment of the problem is needed. The modeling of the radiative transfer relies on the discrete ordinate method [Dembele, Delmas, and Sacadura (1997)]. When considering only two directions, the so-called Two-Flux model is applied to water spray shielding [Prétrel, H. and Buchlin (1994), (1996)]. It consists of a system of two equations describing the variation of the spectral hemispherical intensity transmitted in the forward direction \( I^+ \) and in the backward direction \( I^- \). Their variation is expressed in the following form:
\[ \nabla I_h^+ = \left( K_{a,\lambda} + K_{s,\lambda} \right) I_h^+ + K_{a,\lambda} I_{\phi h}^+ + K_{s,\lambda} I_h^- \\
abla I_h^- = \left( K_{a,\lambda} + K_{s,\lambda} \right) I_h^- - K_{a,\lambda} I_{\phi h}^- - K_{s,\lambda} I_h^+ \]

The absorption coefficient \( K_{a,\lambda} \) characterizes the efficiency of the gas and the droplet-phase in absorbing the thermal radiation of wavelength \( \lambda \). The scattering coefficient of the liquid phase, \( K_{s,\lambda} \), is the fraction of the energy scattered in the direction opposite to the propagation. Both coefficients are a function of the liquid refractive index, droplet density and droplet cross-section.

The one-dimensional version of the complete thermohydraulic model leads to a system of \( 8+4n_d \) ordinary differential equations solved by a Runge-Kutta 5th-order algorithm with adaptive stepping. The most costly exercise is the calculation of the thermal radiative shielding because it demands a spectral calculation: a typical simulation of a spray curtain, 4 m long, described by 10 droplet classes requires about 1 minute of CPU time on a DEC-Alpha workstation.

In fine, the objective of safety engineers is to get the best total attenuation. The shielding system of thickness \( L \) intercepts a thermal radiation of intensity \( I_{\lambda}(0) \) that characterises the energy emitted by the fire and let passing through the forward spectral intensity \( I_{\lambda}(L) \). Thus, the following relation defines the total attenuation factor:

\[ A = 1 - \left[ \frac{\int_0^{\infty} I_{\lambda}^+(L) d\lambda}{\int_0^{\infty} I_{\lambda}^+(0) d\lambda} \right] \]

### 3.2 Impinging spray curtain

The numerical simulation performed with the engineering 1D model shows that the total radiative attenuation afforded by the water mist phase can be satisfactorily
approximated in a macroscopically way by the Beer-Lambert law. In such a formulation, the optical thickness $\kappa_{dp}$, which mainly depends on the size and concentration of the water droplets, may finally be expressed as follows:

$$\kappa_{dp} = \frac{3}{2} \frac{\dot{m}_{t,u}}{\rho U_d SMD}$$

(9)

Where $U_d$ is the mean droplet velocity in the spray; solving the droplet motion equation shows that $U_d$ decreases with the distance from the nozzle to reach quickly its terminal value.

Therefore, equation (9) may model the radiative process in the spray region of the impinging curtain [Hald and Buchin (2003)]. The attenuation due to the liquid film follows the same approach. Noting that the optical thickness varies along the wall since the film thickness, $\delta(z)$, increases monotonically with the vertical coordinate $z$, the total attenuation factor due to liquid film is written as:

$$A = 1 - e^{-a_1 \delta(z)}$$

(10)

Where $a_1$ is the extinction coefficient of the water determined experimentally during dedicated preliminary tests performed on a vertical flat plate instrumented with fluxmeters and triangulation laser probe for thickness measurements [Buchlin (2001)].

The downward evolution $\delta(z)$ is predicted by means of a turbulent falling film model leading to the following simple analytical relation [Hald and Buchin (2003)]:

$$\delta(z) = \left[ \frac{\Gamma \cdot z}{B \rho} \right]^{\frac{1}{\gamma - 1}}$$

(11)
Where $\Gamma$ is the mass flux impacting on the wall. The value of the constant $B$ and the exponent $\gamma$ depends on the flow regime.

Finally, the total thermal shielding provided by the impinging spray curtain is given by:

$$A = 1 - e^{-\kappa_{dp} e^{-a\delta(z)}}$$  \hspace{0.5cm} (12)

### 4. Laboratory experiments

The thermal radiative shielding experiments by a water spray curtain have been conducted on the VKI Water-Spray facility, which allows the testing of industrial nozzles with flow rates up to 1 kg/s at 800 kPa of discharge pressure. A general view of the set-up is shown in figure 2.

Propane burners simulate a source of 14 kW at 1000 K. A dedicated IR concentrator distributes a uniform radiant flux of 11 kW/m$^2$.

The water curtain is formed by ramps equipped with a nozzle density varying from 10 to 33#/m. The nozzles are of full cone type from Spraying Systems with an orifice diameter of 0.51 mm and a flow number $F_n=6.57 \times 10^{-6}$ kg/s $\sqrt{\text{Pa}}$. The test rig is equipped with a flowmeter and pressure transducers to characterise the global flow conditions. The operating pressure ranges between 200 and 700 kPa. Spray characteristics have been measured by a Phase Doppler Anemometer. The droplet diameter fits to a Rosin-Ramler distribution with a Sauter mean diameter ranging from 50 to 200 $\mu$m. The droplet velocity may vary from 3 to 15 m/s.

The attenuation performance is deduced from heat flux measurements obtained with Medtherm radiometer. This probe is a thermopile equipped with a Schmidt-Boelter sensor. It measures a temperature difference proportional to the received heat flux. To eliminate the convection effect, a RRS-5 window transparent in the spectral range 1 to
40 µm, is positioned few micrometers in front of the sensitive surface. In case on impinging spray, three ZnSe windows of 0.05 m in diameter and vertically spaced of 0.15 m are flush-mounted on the target wall. A Medtherm radiometer is placed behind each ZnSe window.

5. Field Tests

In the frame of collaboration between the ASTRRE consortium partners, campaigns of full-scale experiments have also been conducted to evaluate the water curtains in real like industrial conditions [Lieto (1997)].

A first series of trials have been performed in 1996 on a GDF site located at Saint Etienne de Montluc near Nantes (France). Fires of few decades of kW/m² were produced in a LNG pool of 2 m wide and 25 m long. Flame height of 6 m has been observed. Two parallel curtains located at 5 m from the LNG pool have been mounted for the tests. The first curtain, 5 m long, is composed of full-cone nozzles of LECHLER FC3 402 962 type located at 5 m from the ground and fed by 250 kg/min. of water. The second was 2.25 m long and positioned at 4.2 m from the ground. It is made of 44 TG03 Spraying System full-cone nozzles equally distributed (≈ 0.15 m) on a 3-pipe manifold; the mass flow rate was 11 kg/min. Four fluxmetres are positioned 5 m after the curtains in the pool and water curtain axes. One fluxmeter is a Medtherm radiometer, the three other have been developed by the CETHIL [Chantrenne and Raynaud (1996)]. Figure 3 shows a view of a LNG fire test with curtain operating (a) and the design of the spray boom tested (b).

The second series of trials was conducted in 1997 on the GESIP site, near Vernon (France). The objective was to evaluate the shielding performance of water curtains in case of unleaded petrol fires. About 1000 litres of fuel was put in fire in a circular
basin of 2.8 m in diameter. The water barrier is constituted by four downward FC3 nozzles placed with a spacing of 0.75m at 4m from the ground. It is completed by a mobile upward curtain made of one 180° hydroshield nozzle set at the ground. The downward system may debit 80 kg/mn.m under 700 kPa and produces a curtain of about 4m long. When operating at 600kPa the hydroshield nozzle yields 400 kg/min. and forms a peacock tail covering a zone of 8m. During these tests the wind speed measured by the SEP meteorological station near the GESIP site, reached values as high as 4m/s to 5 m/s. To avoid that the wind carries important amount of water to the fuel basin and perturbs the combustion, the water curtain was oriented 45° with respect to the wind direction. The same measurement technique than for LNG tests is used.

6. Typical Results

6.1 Vertical curtain

The radiative shielding provided by a vertical water-spray curtain is exemplified by the spectral intensity distributions predicted by the 1D approach as plotted in figure 4. Likening the fire to a blackbody at 1125K (continuous thick curve), figure 4 shows the regions of the infrared spectrum affected by a water curtain composed of water droplets with a mean diameter of 165 µm and satisfying a Rosin-Rammler distribution. The particular shape of the transmitted spectrum is the result of the complex variation of the refractive index of the water with the radiation wavelength. The contribution of the gas phase to the shielding, mainly coming from the vapour produced by the droplet evaporation, concerns only narrow bands as depicted in figure 4 (thin line) and represents only a small fraction of the global attenuation.
This is confirmed by plotting in figure 5 the vertical distribution of the total-attenuation factor. At the top of the curtain, as the spray develops, the air entrainment slows down the droplets and leads to an increase of the liquid concentration (region I). The net result is an augmentation of the thermal attenuation. Then, when the spray is fully developed the attenuation factor does not evolve any more (region II). Finally, after a certain axial distance, the effect of the droplet evaporation becomes noticeable and the shielding performance lessens (region III). It is worth remarking that the vapour production due to the water evaporation does not counteract the loss of the droplet interfacial area.

Figure 6 summarizes a comparative exercise between the numerical simulation and the laboratory experiments [Pretrel and Buchlin (1996), (1997)]. The 1D spray model reproduces satisfactorily the laboratory tests. The increase in pressure has a benefit influence on the attenuation performance. Such an effect results mainly from the decrease in the droplet size (see Eqs (2) and (9)), which leads to an increase of the droplet concentration and consequently an augmentation of the total surface opposed to the radiation, and of the back scattering (only from tiny droplets). The augmentation of nozzle number is also a way to increase the droplet density and then to enhance the shielding factor of the curtain. However, figure 6 points out that the water curtain is more efficient at high pressure and at moderate number of nozzles than with low pressure and numerous nozzles. Such a behavior is a direct consequence of the additional effect brought by the pressure through the reduction of the droplet size.

As expected, the addition of nozzle lines in the curtain improves the attenuation. It contributes to increasing the effective optical path. However, for design purposes it is
worth comparing the shielding produced by a multi-ramp curtain to a barrier formed by the same number of nozzle lines, \( N_r \), but now working independently (that corresponds to a very large line spacing \( E_h \)). Then, an enhancement factor \( F_A \) may be defined as the ratio of the attenuation provided by a multi-ramp curtain to that resulting from \( N_r \) independent ramp curtains. The finding is plotted in figure 7. It indicates a loss of efficiency of the multi-ramp curtain when the distance between the lines is smaller than one-half the spray diameter, \( D_s \). In such a situation the spray-to-spray interaction has a detrimental effect on the droplet concentration because the air entrainment is high and the small droplets move faster (final low droplet concentration). Above this critical spacing-value the enhancement factor exceeds the theoretical limit of 1. This unexpected behaviour is the result of the formation of an additional mist due to the accumulation of the very tiny droplets within the recirculating gas flow between the different spray lines. Obviously \( F_A \) should drop to 1 for high values of \( E_h /D_s \).

Figure 8 shows a typical radiometer signal recorded during a LNG field tests. The shielding effect offered by the water spray curtain appears clearly since a mean attenuation of about 70% may be estimated. Figure 9 gathers the field tests results. It is worth remarking that attenuation factor as high as 75% may be reached for linear flow rate ranging from 60 to 120 kg/min.m. The comparison between the field test data and the 1D simulation reported in table 1 bears out that the 1D approach is able to predict thermal shielding in industrial situation. The agreement improves as the pressure increases.
6.2 Impinging curtain

The nozzle arrangements tested for the impinging curtain configuration, are composed of three vertical ramps of 15 TG03 nozzles spaced by 3cm as shown in figure 2b. In a loose arrangement, the spacing between the vertical nozzle rows is 0.5m and the sprays at the impact on the wall do not overlap. In this case, the liquid mass flux varies from 0.07 to 0.12 kg/s.m². In a dense arrangement, the reduction of the row spacing to 0.25m leads to spray overlapping. The liquid mass flux is now ranging from 0.11 to 0.18 kg/s.m². An important parameter, which controls the casing performance, is the standoff distance, Y, between the nozzles and the wall. Figure 10 emphasises the effect of Y on the total attenuation factor. The A-value plotted here is the mean calculated as the average of the output of the three radiometers with the bar of variation indicated. Two different behaviours are noticed. Within the loose arrangement, a small standoff involves the presence of zones poorly wetted and the resulting attenuation is weak. Notice that the size of the bar variation typifies the non-uniformity of the water covering. As the nozzles move away from the wall, the spray impingement area augments and the shielding improves. For the dense arrangement the uniformity of water blanketing is of very good quality and the resulting attenuation factor is very high. In such a situation, the standoff distance has a no significant influence on the final shielding performance.

The radiative shielding model presented in section 3.2 is now used to simulate the experiments carried in laboratory. Figure 11 displays a typical comparison between of the prediction and the experimental data. In the upper region, the model under predicts the experimental observation because it does not reproduce the eventual effect of the splashing at the spray impact which leads to the existence of an upward
liquid film. Otherwise, the agreement can be considered to be very satisfactory considering the simplicity of the proposed model.

7. Typical industrial application

To exemplify the applicability of thermal shielding by water spray curtains to industrial situations, the following scenario is considered. A storage tank, 20 m high and having an outer diameter of 20m, receives a radiant heat flux of 60 kW/m² from a fire at 1300K. To protect the total integrity of the tank, two shielding approaches are envisaged.

The first project consists in installing several circular water curtain ramps at different altitudes on the tank. The available downward pointing nozzles that form sprays are of full cone type with a flow number of $F_N = 9.7 \times 10^{-4} \text{ kg/s.Pa}^{0.5}$ and an orifice diameter of 6.25 mm. The spacing between nozzles on a given ramp is 0.9 m. The water network allows a discharge pressure of 1000 kPa. The relative humidity of air is 30% and the ambient temperature is 40 °C. The 1D model of thermal shielding by vertical spray curtain is applied.

Figure 12a shows the predicted spectral attenuating efficiency of a spray ramp and indicates that about 61% of the radiation may be screened. 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 12b. 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 hoops at vertical interval of 7m below. Within this arrangement the overlapping of the curtains counterbalances the deficiency of shielding revealed in figure 12. The 1D numerical
simulation indicates also that the curtain retains its hydrodynamic integrity over the 7m distance for wind speed not exceeding 4m/s since most of the terminal velocity of most of the droplet classes is larger than 6 m/s. Finally the total number of nozzles needed is about 210 and the total water flow rate requirement is about 204 kg/s.

The second project relies on impinging sprays. The same nozzles as previously are now oriented horizontally and located at a standoff distance of 3m from the tank. Accepting an overlapping factor of sprays at the impingement of 20% to get good wall wetting, the nozzle spacing becomes 2m in both directions. With such parameters, the number of nozzles on a ramp is 41 and the number of ramps is 10. In this project the water pressure can be readily reduced to 500 kPa so that the total water flow rate is 281 kg/s, which corresponds to a mean mass flux of 0.22 kg/s.m². Based on such a design the theoretical model predicts the vertical attenuation factor distribution plotted in figure 13. Very high shielding performance comes out for about the same water consumption demanded by vertical curtain project.

8. Conclusions

Water spray curtain to protect storage tank from fire radiation can be an efficient thermal shielding technique.

Theoretical models to design such a mitigation device, supporting laboratory experiments and field tests are presented and illustrated.

The curtain can operate vertically downward and be installed around the tank to be protected. The efficiency increase as the number of nozzle ramps within the curtain
increases. Attenuation factor of 50% to 75% can be expected. A typical mass flow rate per curtain meter anticipated is 2 kg/s.m.

Water spray curtain impinging on the wall leads to higher shielding performance. Taking advantage of the formation of a falling water film continuously refreshed by the spray impaction, such a technique is able to bear attenuation values as high as 90%. The design of such a system requires nozzle-to-wall standoff distance, which ensures sprays overlapping and is typically characterised by water mass flux around 0.15 to 0.25 kg/s.m².

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References


Figure 1: Thermal shielding by water spray curtain for storage tank protection
(a) Vertical configuration  (b) Impinging configuration

Figure 2: Thermal shielding experiments
(a) LNG fre with thermal shielding          (b) spray curtain design

Figure 3 : View of a LNG test
Figure 4: Spectral attenuation by vertical water curtain
Figure 5: Vertical distribution of the total attenuation
Full cone spray TG03

Figure 6: Attenuation factor with a single ramp curtain
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Figure 8: Radiative heat flux without and with shield by vertical water curtain
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Figure 11: Theoretical-experimental comparison of attenuation factor by impinging water curtain.
Figure 12: Typical attenuation factor by a vertical industrial curtain
Figure 13: Typical attenuation factor by an impinging industrial curtain.
Table 1: Attenuation factor: Field test-1D model comparison

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