Radiative shielding by water mist: comparisons between downward, upward and impacting injection of droplets

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Abstract. Radiative shielding with water curtain has been studied numerically, investigating three different possibilities of droplet injection: downward, upward and impacting on a wall to be protected. The efficiency has been evaluated based on radiation attenuation predicted considering a given incident flux attenuated when crossing the area where water is injected. For upward and downward injection, a simple water curtain is considered. For the impacting spray case, a water film streaming on the wall is considered in addition to the spray (an idealized film with constant and fixed thickness for the moment). The dynamics has been imported from an Eulerian-Lagrangian simulation and radiative transfer has been addressed with a Monte Carlo method. Results show that the upward injection performs better than the downward injection due to a favoring dynamics that increases the residence time of droplets. The impacting spray could be even more efficient owing to the possible high attenuation efficiency of films, but present results still make use of simplifications on the water film falling on the wall and present promising observations require further verification.

1. Introduction

Water droplets injected in air may be used to build a radiative shield which can attenuate radiation coming from a radiative source like a fire or a high temperature process for example. The attenuation mechanisms are well known: absorption by droplets and vapour in air, plus scattering due to the droplets solely. This has been studied for decades (see [1–5] among others) and in particular by present authors during the last ten years. A numerical code - BERGAMOTE - has been developed, which simulates the two phase flow made of droplets in wet air with an Eulerian-Lagrangian approach and which predicts the radiation attenuation through this medium using a Monte Carlo method. The code has been validated in some situations of a single spray and further extended to a series of sprays in classical configurations of a downward injection of the droplets [6, 7]. Some preliminary predictions also indicated that a better use of the water - a better radiation attenuation - could be achieved if droplets are injected in a different manner in order to increase the residence time of droplets in air. This idea is further extended here with a shield aimed at protecting a given surface, comparing different injection possibilities: classical
downward injection, or upward injection, or impacting sprays on the surface to be protected. The
guiding idea with the upward injection has been already discussed in [8]: the double use of the
droplets with their up and down motion leads to a stronger attenuation ability. The drawback is
a weaker stability of the water curtain however, which can be dispersed by an air flow due to wind
or a ventilation device for example. With the impacting spray, the goal is to take benefit from
a first spray attenuation which is completed by the influence of a streaming film on the surface
which also weakens the incident radiation on the surface. This direct protection of a surface
could be more efficient than a simple use of a water curtain in front of the surface to be protected.
Such idea was also suggested by Hald and Buchlin [9]. These different solutions of water injection
for radiation attenuation have been studied numerically in the present work. Water with given
droplet size distribution and flow rate is injected in air, trajectories are computed involving
evaporation, turbulence and heat transfer phenomena. Then, radiative properties of the spray
are calculated in the whole computational domain, combining the Mie theory and a C-k model,
in addition to a direct computation of transmission through a water film for the impacting spray.
A Monte Carlo method is used to calculate the radiative fluxes in order to predict the potential
radiation attenuation of the resulting medium by dividing the radiative flux reaching a given
target, with the reference value obtained in the same configuration with the spray off. With
the impacting spray, some assumptions are required regarding the film thickness which makes
the study still exploratory, but the high attenuation potential of such a film makes this method
very attractive. The following sections will include a short description of the spray dynamics
with some details regarding the droplet trajectories, which will help to understand the radiative
properties of the medium. Then the focus will be put on radiative transfer results in a second
step. They will be discussed in terms of transmission and attenuation ability.

2. Spray dynamics
Details regarding the Eulerian-Lagrangian process used for the present simulation have been
already presented and validated in [6–8]. Without describing the various submodels, the involved
physical phenomena are recalled here: drag and gravity effects, convection and evaporation
influence on the heat transferred to the droplet, influence of the turbulence on the droplet
trajectories through a dispersion model, influence of the dispersed phase on the gas phase through
dedicated source terms. Finally two subroutines are run for the Eulerian simulation of the gas
phase with mass, momentum, energy balances plus a k-ε model on the one hand, then balances
for mass, momentum, position and energy for the droplets on the other hand. Interactions
between phases are taken into account through an iterative process.

The strong coupling between dynamics and radiative transfer has been already demonstrated
to be of importance in problems close to the present one [8]. Actually, this is mainly treated
as a one-way coupling in the present work, because the droplet distributions are affecting the
radiative properties of the medium and consequently the radiation propagation. However, the
radiation absorption is not expected to be as strong as to modify the droplet size due to enforced
evaporation process for example. The scenario considers a curtain aimed at protecting a given
target from radiation coming from a high temperature source but not submitted itself to a high
temperature increase (the curtain is aside the emission source, just building a shield against
radiation). A two-way coupling which would consider the alteration of the spray characteristics
due to strong radiation absorption would not complexify the resolution. An iterative solution
between subroutines for dynamics and radiative transfer would solve the problem. For the
present application the absence of coupling will allow us to save time. One has also to mention
that further validation would be achieved at laboratory scale with a reduced incident flux and
little impact on the spray. This would be simulated as a one-way coupling problem too.

For the present exercise the following conditions have been chosen for the spray: the
case of nozzles located on the same pipe, regularly spaced, fed with the same pressure, but
possibly oriented in various directions (as illustrated by Figure 1, red circles show the location of the nozzles in the different configurations). Numerical conditions mimic a nozzle referred as TP400067 by Spraying systems and Co. The pressure feed is 4 bars, the consecutive water flow rate is 0.32 L/min, the droplet distribution can be described by a Log-normal law with mean diameter set to 123 \( \mu \text{m} \) and dispersion coefficient equal to 0.4 at the nozzle exit. The injections provide a series of conic sprays with angles equal to 48 and 18.5°. The injection velocity is 24 m/s. All conditions are assumed to be identical whatever the injection directions: vertical upward, downward, or inclined (an assumption which could be discussed as gravity effects may alter the way droplets are formed and consequently the size distribution at the injection point in particular). In the following sections, results will consequently concern the same water consumption, yet the attenuation ability will strongly vary with the injection type as it will be seen. Supplementary choices must be done regarding the location of the injection points. For the present qualification study a complete sensitivity study cannot be conducted on the role of the various possible injection locations. Arbitrarily (and with the idea of validating the present results experimentally with a device available in our laboratory), the vertical position of the nozzles is 1.50 m in the downward case, 30 cm in the upward case and finally 1 m in the impacting case with an horizontal distance of 1 m between the nozzles and the wall). In this last case the injection angle with respect to the horizontal direction may also have an influence. As a tentative study, an angle of 45° is chosen here, a parameter which could be of course studied and optimized. A series of nozzles in parallel are considered as to generate a water curtain. Nozzles are separated by a regular space of 10 cm, assumed to be fed by a horizontal pipe. In order to describe the spray numerically, a polydispersion is considered with twenty classes between 20 and 300 \( \mu \text{m} \). The classes are automatically generated in order to concern the same water flow rate amount (one twentieth of the whole water quantity for each class).

The computational domain corresponds to a box with the following dimensions $3 \times 0.05 \times 3 \text{ m}^3$, which is extended to a height of 6 m for the upward injection case since a dedicated sensitivity study showed us that small droplets may reach such high positions that the upper wall at 3 m would affect their motion. Symmetry planes are defined considering the series of nozzles and restricting the analysis to the central part of the domain. The width of the computational domain is reduced to 5 cm corresponding to the half space between two neighbouring nozzles. The bottom right subfigure on Figure 1 gives a schematic view of the problem in a case of a downward injection. The emission panel is on the foreground, the target is the rear surface and radiation crosses the spray along the x-direction. Typical mesh involves in that case $48 \times 5 \times 40$ cells for this $3 \times 0.05 \times 3 \text{ m}^3$ domain, with cells tightened near the injection point and in the spray area. For the upward injection, the same configuration is considered except that droplets are injected in the positive z-direction (the mesh becomes $60 \times 5 \times 50$ cells). Finally for the impacting spray, droplets are injected at 45° in the positive x- and z- directions in the original $3 \times 0.05 \times 3 \text{ m}^3$ domain. The other subplots of Figure 1 give a sketch of the droplet trajectories in the different cases (as commented below). For a better visualisation several injections have been plotted using the symmetries, but only one half of a single injection has been computed.

For the sake a brievity, complete numerical conditions are not detailed, but they can be found in [10].

For the understanding of the water curtain characteristics the first key element is the description of the droplet trajectories which affect their residence time and the consecutive absorption and scattering ability of the water curtain. As shown on Figure 1, the droplets are following very different trajectories. Two classes have been chosen for the representation. The trajectories of a collection of droplets are plotted, revealing the spray shape. The classical downward motion of droplets on the upper left subfigure is changed in an up-and-down motion, with strong perturbations induced by the carrying flow, on the upper right subfigure where droplets are injected upward. This is expected to induce a longer residence time. Finally, a
complex trajectory is also observed for the impacting case where small droplets can even be carried away from the curtain area. For the present illustration a condition of no-rebound has been chosen, meaning that all droplets caught by the surface are trapped and provide a deposit. Direct observations by rapid camera have led us to such hypothesis of droplet deposit without rebound (experiments carried out on droplets with similar size but on a cold wall). Droplets escaping at the top of the picture are simply carried away by the air flow deviated in front of the wall. Rebound conditions could be introduced, with possible splash or split which could provide smaller droplets and would be even better from the radiation attenuation point of view since attenuation increases when droplet size decreases (given the water quantity).

The residence time is reported on table 1 for the two droplet sizes whose trajectories have been presented on Figure 1. These are averages obtained on a huge number of droplets of these given classes followed during their trajectories.

As can be seen through table 1, the classical downward injection penalizes the droplet residence time, more especially in what concerns the small droplets (the most efficient ones for the radiation attenuation). The upward injection appears to be the most efficient solution regarding this time criterion, with a gain highly better than a simple factor 2 due to the up
Table 1. Residence time (in s) depending on the injection direction.

| Droplet size | Downward inj. | Upward inj. | Impacting spray |
|--------------|---------------|-------------|-----------------|
| 66 µm        | 0.88          | 12.19       | 4.93            |
| 271 µm       | 0.26          | 2.68        | 2.03            |

and down trajectory. This is due to the fact that droplets first decelerate during their upward trajectory, before falling with a zero initial velocity (whereas droplets in the downward case are injected with a high velocity which leads them very quickly to the floor). The impacting spray still allows a better use of the water, even less satisfactory than the upward case. However, the droplets which are reaching the wall may continue to contribute to radiation attenuation with the streaming film. The present times must be considered with criticism as they are clearly conditioned by the exact geometrical configuration which has not been optimized. An injection at a different vertical position or shifted from, or toward, the wall for the impacting case will affect the numerical results. Yet, the present comparison of table 1 still allows a qualitative understanding of the various injection efficiencies.

3. Radiative transfer simulation
3.1. Transfer through the water curtain

Radiation is supposed to come from a radiant panel like it is presented on the schematic view on Figure 1. The case of a panel behaving like a blackbody at 1000K has been treated here.

Radiative properties are simulated as in [6]. Without recalling the details, Mie theory is applied assuming that droplets are spherical and using the optical indices for water given in Hale and Querry reference paper [11]. The radiative properties for gases (water vapor and carbon dioxide) are modelled with a classical C-k model with 43 bands as presented in [12], except for one representation below, where properties will be finally post-processed in the form of averaged values on bands following a 367 band discretisation for a finer description of the properties.

A Monte Carlo method is used for the simulation of radiation propagation, neglecting emission inside the spray still considering that the heat source does not induce a relevant spray heating. A huge number of quanta are followed in the domain, with a numerical process based on a distance of interaction computed with the scattering coefficient. The exact number of quanta of course depends on the information required (spectral or total flux) with convergence criteria based on the variance of the local flux received by the target. Using the droplet distribution, absorption coefficients are computed in the whole domain and the absorption of the quanta is accounted for until their total absorption or their escape from the domain. Results are finally obtained considering the number of quanta received on the target surface. Details on the specific sensitivity study may be found in [10].

Results for the radiative properties are commented first. Based on the distributions predicted with the simulation of the dynamics, the size distribution and the volumetric fractions for droplets and vapor are known. Then, the radiative properties may be computed for each phase. A simple additivity is considered for the prediction of the curtain radiative properties. Typical radiative properties are presented on Figure 2 for the present nozzle under a pressure of 4 bars. For better illustrating the variations a fine representation based on a 367 band formulation has been chosen as explained above. Coefficients are averaged on each band in order to show the attenuation coefficient as a function of the wavelength. For the rest of the simulation a classical
Figure 2. Absorption and scattering coefficients yielded by a single nozzle TP400067 under 4 bars

C-k formulation for the gases with a 43 band resolution has been observed to be sufficient for an accurate description of the spectral attenuation by the spray. As can be seen the attenuation by the droplets is possible in the whole infrared range. Absorption and scattering have a similar influence in the low wavenumber range, then absorption falls to very small levels and scattering is the main effect in the larger wavenumber range. This can be of importance since scattering is highly forward oriented for droplets with size really larger than the wavelength. As a consequence the effective attenuation may be limited despite a high attenuation in terms of coefficients. This is especially the case for applications where sources and targets have a large emission or reception surface, like in the present case. One can also note the contribution of gases (H$_2$O and CO$_2$) on the figure. They do not contribute as the main attenuation cause, yet they will affect the curtain efficiency.

Using the Monte Carlo simulation a flux received by the target from the source can be computed in the absence of the spray for a reference value and then with the spray on. The ratio of the two values provides a kind of transmissivity for the curtain:

$$T_{curtain} = \frac{\text{Flux computed through the spray}}{\text{Reference flux without spray}}$$ (1)

Attenuation is defined as the complementary value to 1 and finally total values can be computed applying Planck’s averaging for example. Following results will make use of these different definitions.

The resulting spectral transmissions through the water curtain are shown on Figure 3 considering the different injection possibilities and at different vertical positions on the target panel. Comparing the three subfigures, the differences between the three injection solutions are obvious.

One can first comment the results for the downward injection as our reference value. The mean transmission level is around 80% with a little decrease when going down in the curtain (because droplets are decelerating and their residence time becomes higher near the bottom). The global evolution as a function of the wavelength is not strong. Yet, there is an increase in the transmission for larger wavenumbers (which is in fact more pronounced for the other injection
Figure 3. Spectral transmission through the water curtain produced by the droplet injection directions). As above-explained the extinction coefficient of the droplets is quite constant, but for high wavenumbers absorption falls to a near zero value due to the low absorption index of water. It appears that scattering alone is less efficient for an actual attenuation of radiation in the present scenario where the target is wide. There is a deviation of radiation from initial direction due to scattering, but as scattering is highly forward oriented the deviation is weak and the target still receive the incident flux. It is not really protected and the attenuation ability is finally weak. For the downward injection the attenuation level reaches values close to 25% (transmission equal to 75%) near the bottom of the curtain where droplets have already decelerated. In the upward injection case the attenuation ability is of course better, in relation with a higher residence time for droplets. Transmissions down to 20% are predicted in the best case (low wavenumbers) for the same water consumption. The transmission is higher in the high wavenumber range but the water use remains more efficient than in the downward case. Finally, the impacting spray provides attenuations in an intermediate range. For this particular case, transmission strongly varies with the vertical position, which could be related to the droplet dynamics. The best attenuation occurs near the impacting area where droplet concentration is the highest. Of course the total attenuation in the impacting case is expected to be even better.
3.2. Water film description

One major difficulty is the prediction of the actual thickness of the film, which is an exercise of fluid mechanics beyond the scope of the present paper aimed at comparing the different strategies and at defining if a gain can be achieved by using water in a different manner than being simply downward injected. Therefore the film is treated aside from the rest of the spray dynamics, assuming a constant thickness. It is clear that its thickness should vary with position as a consequence of its streaming on the wall. In order to make the evaluation possible the thickness is set to an arbitrary value (which will be varied in order to see the sensitivity of the results to this parameter). Then, the absorption of this homogeneous semitransparent medium is simply defined on the basis of the optical indices of water. The transmissivity of the film is given by:

\[
T_{\text{film}} = e^{-4\pi k \nu \delta}
\]  

where \(k\) is the absorption index for water (taken from the database by Hale and Querry [11]), \(\nu\) is the wavenumber and \(\delta\) is the film thickness.

The complete transmissivity through the spray plus the film will be finally defined as the product:

\[
T_{\text{total}} = T_{\text{film}} \times T_{\text{curtain}}
\]

Corrections for the reflection at the water film surface are not considered at this stage where the film thickness is already a rough assumption which mainly affects the results. Figure 4 presents the spectral transmission through an idealized water film. Small thicknesses have been considered (between 10 µm and 1 mm) but the potential gain in attenuation is very high as compared to what dispersed water can do. Of course one can ask if a film with thickness as small as 10 µm can be produced in an homogeneous layer but owing to the high attenuation ability of a film, this technique could be considered as an actual way to better use water and to add a supplementary shielding effect to the spray.
4. Radiation attenuation efficiency

For a complete comparison of the three strategies, efficiency results are now plotted on Figure 5, with the resulting spectral transmission for the downward, the upward and the impacting case in association with an arbitrary film thickness (of course, this assumption of an homogeneous film with given thickness must be kept in mind). The scenario of a radiant panel illuminating a target panel through the spray is kept and the transmission is seen at two different heights on the target: 10 cm and 130 cm above the floor respectively. It is confirmed for both vertical positions that the upward injection highly increases the shielding ability of the curtain, by a factor between 3 and 4, as compared to the downward injection. The efficiency of the impacting curtain is between the two above results, of course potentially highly improved by the film action. The exact ability is dependent on the guessed film thickness but the attractivity of the solution is obvious.

Further analysis can be done on the total transmission which is plotted as a function of the vertical position on Figure 6.

**Figure 5.** Spectral transmission with the different injection solutions at two vertical positions

**Figure 6.** Total transmission through the water curtain as a function of the vertical position
The results have been computed with a Planck’s averaging considering a 1000 K blackbody source. As above observed the behavior of the impacting spray is in between the results provided by the downward and the upward injections. Near the bottom of the curtain, the spray solely does not present a clear improvement as compared to the downward case. However, the attenuation efficiency increases with the height in the spray, reaching performances as high as the one of the upward injection. Moreover, even a very thin water film may improve the attenuation ability in a spectacular manner. A theoretical transmission below 10 % is even predicted if a film thickness of 100 µm can be maintained on the surface of the target wall. Of course, this assumes a steady film, with no heterogeneity, but this seems to be a promising and efficient use of water. A possible supplementary advantage is that the stability of the impacting curtain could be better than the one of the upward solution, which can be quickly dispersed by a lateral air flow (like a wind effect or a ventilation flow) as it has been shown in [8].

5. Concluding remarks

A numerical study has been conducted on the ability of a water curtain to build a shield against radiation, considering three different strategies for injecting water with given nozzles: downward for a high vertical position, upward from the bottom, or directly impacting on a target to be protected. Simulations for radiative transfer through the curtain have been carried out on the basis of results obtained for the spray dynamics with an Eulerian-Lagrangian code. Strong assumptions have been considered at this stage for the film created by the impacting spray however, which is still assumed to be homogeneous with given thickness. Comparisons conducted on a scenario of a radiant panel illuminating a target panel through the curtain show that the upward solution should be preferred if the spray solely is considered, as this configuration provides the highest attenuation through the curtain. However, the impacting curtain is also improving the classical use of water as compared to the downward configuration. Moreover, despite the present assumption of a guessed film thickness, it is obvious that even a very thin film (less than 1 mm or even 100 µm thick) highly attenuates radiation. Considering both the impacting spray and the film, the attenuation quickly appears to be even better that in the upward case. As the stability of the impacting curtain would be probably better than the easily dispersed upward spray (which could be confirmed by a further study on the spray dynamics in that configuration when submitted to a lateral air flow), this impacting strategy should be further studied with a true evaluation of the film thickness and an experimental validation in various conditions.

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