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A Thermodynamic Examination of the Extinguishing Properties of Water Spray and Water Mist

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Abstract

Water-based extinguishing systems as water mist and water spray get increasingly important on the extinguishing market. This work examines the extinguishing properties of these systems on a thermodynamic basis and shows both their advantages and restrictions. The possible extinguishing efficiencies are compared to those of conventional gas extinguishing systems, which are standardized in international guidelines. Based on these results, system solutions are proposed for the protection of rooms, for a local protection of industrial objects and for tunnel applications.

Nomenclature

A	area	$[m^2]$
c	concentration	[Vol-%]
c	constant	[-]
c_p	specific heat capacity	[J/kg K]
c_W	friction factor	[-]
F_R	friction force	[N]
g	gravity	$[m/s^2]$
Δh	evaporation enthalpy	[J/kg]
M	mass	[kg]
m*	mass flow rate	$[kg/m^2 s]$
p	pressure	[Pa]
Q*	heat flux	[W]
r	radius	[m]
T	temperature	[K]
t	time	[s]
v	velocity	[m/s]
x	mass fraction	[-]

α	heat transfer coefficient	$[W/m^2 K]$
β	mass transfer coefficient	[m/s]
λ	heat conductivity	[W/m K]
ρ	density	$[kg/m^3]$

Subscripts

D	droplet
Ext	extinguishing
F	flammability
FL	fire load
G	gas
R	reaction
Sat	saturation
H20	water
O2	oxygen

1 Introduction

Because of the worldwide restriction of the usage of halons, the extinguishing industry concentrated more intensively on the enhanced development of water extinguishing technologies. A common method is to upgrade the sprinkler technology to systems with higher pressures and special nozzles, in order to control a fire with a droplet spectrum, which has a distribution of droplet diameters, significantly different from that produced by ordinary sprinkler nozzles.

The spraying, respectively splashing of the extinguishing agent water has the objective to approach the extinguishing efficiency of gas extinguishing systems. Extinguishing gases have the indisputable advantage to be able to extinguish “around the corner”. This means, that the position of the gas discharge nozzles can be more or less independent from the position of the fire.

The development of the water mist technology finally shall provide a solution, which is not only capable to control the fire over several minutes, but which also does extinguish the fire. Fire tests with water mist systems have shown, that depending on the test set-up and the applied technology, it is not impossible to reach this goal.

The following work examines the thermodynamic conditions, which water spray and water mist must fulfill, in order to extinguish fires safely and how these results can be transferred into solutions.

2 Gas Extinguishing Systems

Gas Extinguishing Systems are well known for decades and have proven their capability to extinguish fires of any fire class safely. The experience won with these systems has entered internationally accepted regulations and guidelines such as ISO 14520, NFPA 12, NFPA 2001, CEA 4007 and CEA 4008.

In principle the extinguishing gases are divided into two types; natural and so-called chemical gases. The natural gases used in extinguishing are nitrogen, argon, carbon dioxide and mixtures of nitrogen, argon and carbon dioxide. As chemical gases Halons, HFC 227ea, FK-5-1-12 and other HFCs are known.

The extinguishing mechanism of both gas types is mainly the inertisation, thus the reduction of the oxygen concentration. While the natural gases inert the whole protection zone, the inertisation effect of chemical gases is more sophisticated. A gas molecule entering the fire zone is split up into its components (atoms) and reduces so the oxygen concentration only locally in the reaction zone according to the ideal gas law. After leaving the fire, the atoms recombine to new molecules. Therefore the necessary extinguishing concentrations are much lower for chemical gases.

In addition to the inertisation effect, there is a certain contribution to the extinguishing by the specific heat capacity of the molecule in case of natural gases and by the energy of the molecule decomposition and restructuring in case of the chemical gases. Therefore the concentrations among the natural gases differ to some esxtend.

The necessary extinguishing concentration and thus the necessary oxygen reduction is only depending on the risk and not on the system hardware used. The following table gives some extinguishing concentrations for nitrogen and HFC 227ea accepted by the last ISO-meeting in September 2002 for ISO 14520.

	Nitrogen [Vol-%]	**HFC 227ea [Vol-%]**
Class A (wood)	30.0	5.8
Class B (n-heptane)	33.6	6.9

Extinguishing Concentration according to ISO 14520

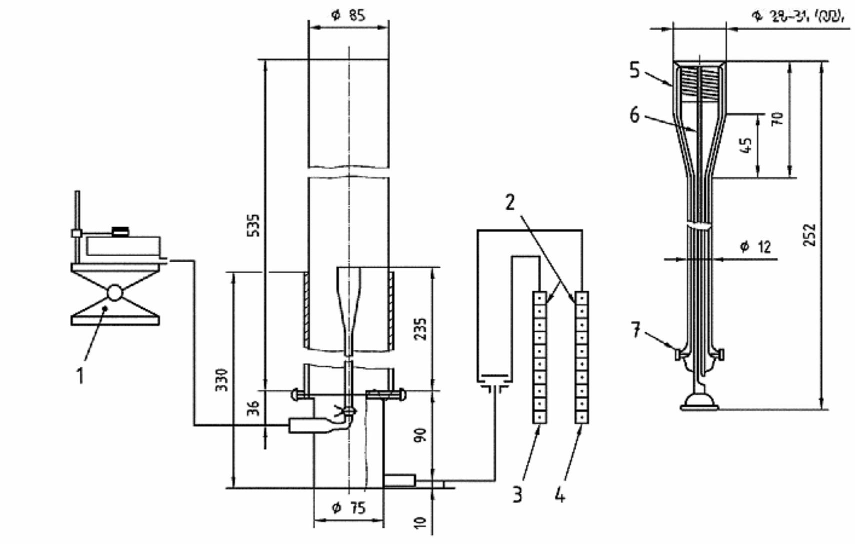
The resulting residual oxygen concentration can be determined by

$$c_{O2} = 20.8 - 20.8 \cdot \frac{c_{Ext}}{100}, \qquad (1)$$

and is found in the range of 13 to 15 Vol-%.

The methods for determination of these extinguishing concentrations are standardised in ISO 14520. For combustible liquids, the cup-burner method can be applied (see figure 1). The burning liquid is passed in glass tube by a mixture of air and extinguishing gas. For other combustibles, there is the possibility of room extinguishing tests with standardised procedures and room sizes. A CEA-report gives information of the experiments and results for most relevant combustibles [1].

The flooding time for natural gases is defined to be 60 seconds, while chemical gases have to be discharged within 10 seconds. To guarantee the necessary safety with regard to room integrity, changes of fire load etc., the extinguishing concentrations given above are multiplied with a safety factor of 1.3 to achieve the design concentrations to be used in actual extinguishing installations. The table gives the design concentrations according to the extinguishing concentrations mentioned above.



a) Cup burner and test fuel reservoir

b) Details of heated cup

Figure 1: Cup-Burner Test

	Nitrogen [Vol-%]	HFC 227ea [Vol-%]
Class A (wood)	39.0	7.5
Class B (n-heptane)	43.7	9.0
Electronic Risks	41.5	8.5

Design Concentration according to ISO 14520 (latest revision)

The objective of this short excursus on gas extinguishing systems was to remind of the high standardisation on the resulting high degree of safety, which has been achieved at least for room protection. Water based can only be an alternative to gas extinguishing system or even replace it, if it can guarantee the same objectiveness in design and the same safety as gas extinguishing systems do.

3 Water Mist Technology

3.1 Extinguishing Capability of Pure Water Mist

The extinguishing effect of water mist is similar to that of extinguishing gases. Water droplets and water vapour are entrained into the fire zone, where the resulting evaporation causes a reduction of the oxygen concentration and so an inertisation effect. In the following the necessary water concentration for extinguishing is estimated and compared to the thermodynamic realistic water concentrations built up by water mist extinguishing systems.

Minimum water density

On the basis of experimental work and theoretical simulations at VdS Cologne [2], the minimum amount of water was determined, which is necessary in the supply air of a fire in order to extinguish it. The following figure shows the result in dependence on the size for a polypropylene fire:

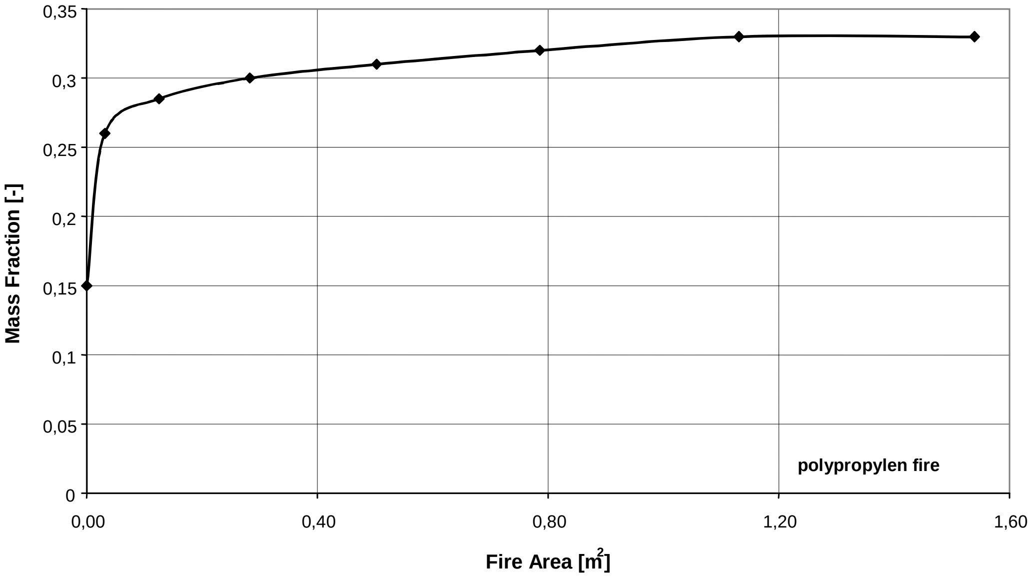


Figure 2: Necessary water amount in the supply air depending on fire size [2]

The mass fraction is defined as follows:

$$x_{Water} = \frac{M_{Water}}{M_{Water} + M_{Gas}} \tag{2}$$

The research work leads to the following results:

- The necessary water mass fraction in the supply air of the fire is depending on the fire size (power of fire).
- Fire with a heat power of more than 1 MW need water mass fraction over 0.3, respectively water densities of 350 g/m^3.

The remaining air mass in the supply air is in case of 350 g/m^3 of water about 820 g/m^3. This leads to a water vapor concentration of about 40 Vol-%. This value is well in line with the extinguishing concentrations of nitrogen (33.6 Vol-%) and argon (39.2 Vol-%). Differences are caused – as explained - by the different specific heat capacities of the molecules.

Physical Properties of Water Mist

Stable water mist, as found in nature in form of clouds, has water fog densities of about 3 g/m^3. In case of higher fog densities, the droplets carried by the air agglomerate and form larger droplets – the cloud is raining out.

In nuclear safety research, large-scale experiments where carried out over the last 20 years in order to examine the aerosol behavior in safety vessels of nuclear power plants. The accident atmosphere contains 20 to 50% vapor and different solved and unsolved forms of dust in case of a major failure. At the CSNI Workshop Paris [3], the results of these experiments were presented.

The test results of different test set-ups were statistically correlated in order to receive the maximum aerosol concentration. The figure shows the maximum measured droplet densities per m^3 for a residence or stability time of one minute.

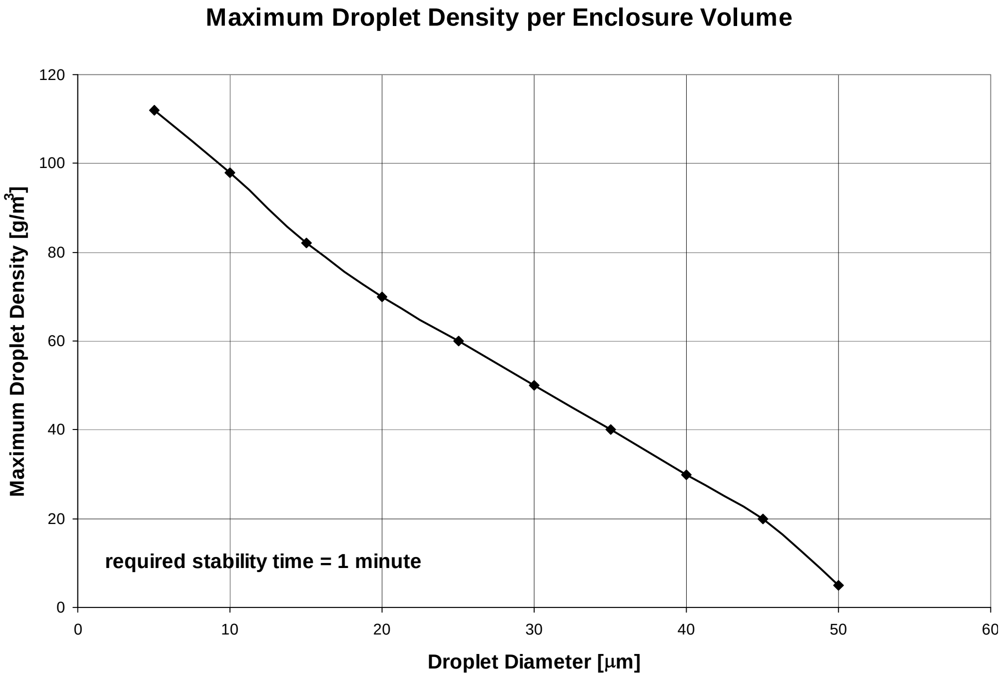


Figure 3: Maximum droplet density as a function of diameter [3]

At the residence time of one minute, which is reasonable for extinguishing, the observed maximum densities were 115 g/m^3 air. For larger droplets between 10 and 20 µm, this value is reduced below 100 g/m^3. The maximum densities are caused by the sedimentation velocities of the droplets.

Vaporized water gives an additional contribution to the water density of the supply air. The dew point line as a function of temperature gives the maximum vapour content of an atmosphere. The next figure shows this curve for vapour/air-mixtures.

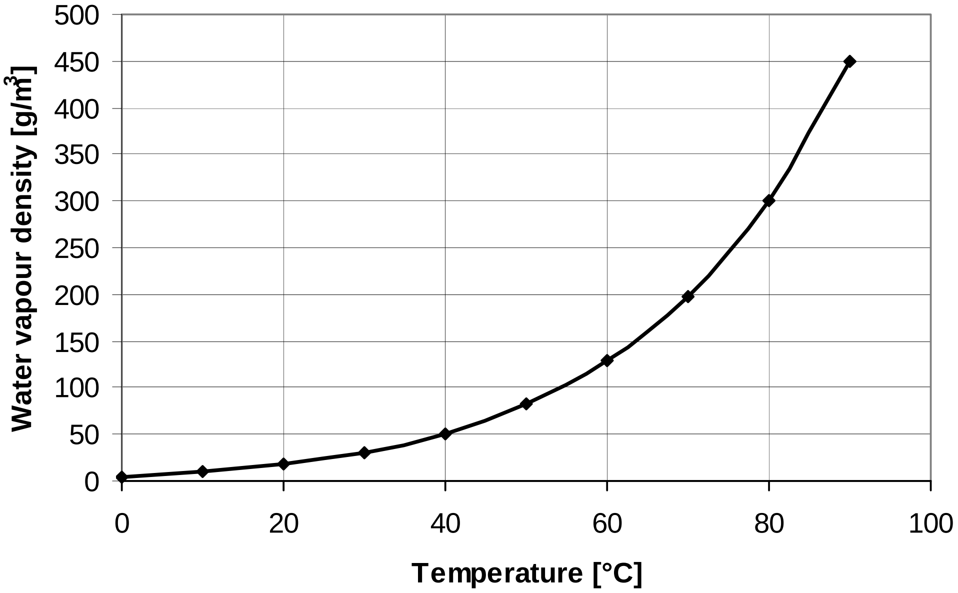


Figure 45: Dew-point line of vapor/air-mixture [4]

The maximum vapor content at 20°C is 20 g/m^3 air. This leads to the following conclusions

- At 20°C a necessary a water mist density a cannot be obtained by the combination of vaporized water and water mist in form of droplets.
- A quasi-static mist, whose droplets are carried to the fire **only** by the supply air, cannot extinguish the fire.
- Water mist systems cannot extinguish fires at ambient temperature safely
- Extinguishing with water mist makes necessary an enclosure; water mist is thus only suitable for room protection.

Only at higher temperatures the water vapor density is increasing to values allowing a secure fire extinguishing. In order to assure the safety level of gas extinguishing systems, this means the possibility to extinguish large fire (= 350 g/m^3 water density) with an additional safety factor, temperatures above 85°C are necessary. Thus water mist system show the same extinguishing efficiency of gas extinguishing systems only at room temperatures, which occur together with huge damages.

3.2 The Siemens Solution

As it is for Siemens Building Technologies unacceptable to use an extinguishing technology, which works reliably only in case of high room temperatures and thus large fires, Siemens decided to add to the water mist a nitrogen discharge in order to overcome the insufficient inertisation capacity of water mist at ambient temperature for room protection. The two extinguishing media are combined in the GasSpray system, what offers the advantages of both:

- extinguishing reliability of nitrogen
- cooling capacity of water mist

The water mist density is calculated risk depending. Its minimum is determined by the objective to cool down the surface of the fire zone from reaction temperature (T_R) below the temperature of flammability (T_F) and to avoid so any re-ignition. The enthalpy equation for this calculation is depending both on the fire load (FL) and the room geometry:

$$M_{FL} \cdot c_{p,FL} \cdot \left(T_R - T_F\right) = \frac{M_{H20}}{A_{Room}} \cdot A_{FL} \cdot \Delta h_{H20} \qquad (3)$$

The mass M_{FL}, which has to be cooled down is depending on the thickness of the heated boundary layer Δz.

$$M_{FL} = \rho_{FL} \cdot A_{FL} \cdot \Delta z \qquad (4)$$

The thickness of the boundary layer, which is heated by the reaction itself, can be estimated in the first order with a standard assumption for the instationary heat conduction:

$$\Delta z = c \cdot \sqrt{\frac{\lambda_{FL} \cdot t}{\rho_{FL} \cdot c_{p,FL}}} \qquad (5)$$

The time t is here the exposure time of the fire on the fire load area. In case of a fully automatic extinguishing, this time does not exceed 100 s. Combining the empiric penetration constant c with the exposure time t to a value k, the following relation for the necessary water amount can be found:

$$M_{H20} = A_{Room} \cdot k \cdot \left(\frac{T_R - T_F}{\Delta h_{H20}}\right) \cdot \sqrt{\lambda_{FL} \cdot \rho_{FL} \cdot c_{p,FL}} \qquad (6)$$

A value of $k \cong 2 - 2.5$ is good approximation.

System

Figure 4 gives a sketch of the principle of the Siemens GasSpray system. The water is stored unpressurized in separate cylinders and discharged by using by-passed nitrogen as a propellant. Both media are flowing through one pipe system and the same nozzles.

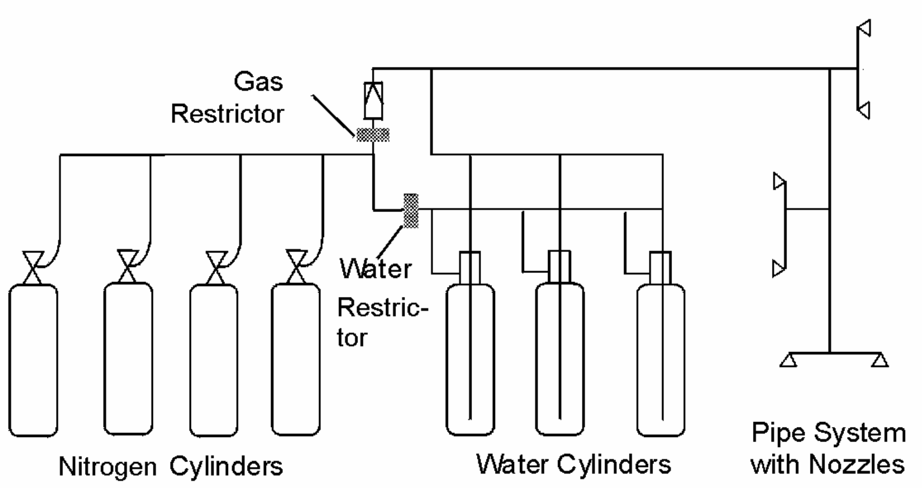


Figure 4: Principle of the Siemens GasSpray-System

Discharging a two-phase flow of nitrogen and water has the additional advantage to be able to work with low nozzle pressures and standard components und avoid cost-intensive high-pressure parts. The water mist and its homogenisation with a droplet size below 50 µm are created by the turbulence of the two-phase discharge.

Nitrogen Concentration

In a first step the nitrogen concentration of GasSpray installations is chosen as in pure nitrogen extinguishing systems according to section 2. In a second step it is planned to examine, if the nitrogen concentration is reducible due to the inertisation capacity of the water mist. With the maximum water density at ambient temperature of 120 g/m^3, a nitrogen concentration of 30 to 35 Vol-% would theoretically be sufficient to achieve the same safety level as with the design concentration stated in section 2. This will have to be proven in a second step with room extinguishing tests according to ISO 14520.

4 Water Spray Technology

4.1 Conventional Water Spray Systems

Conventional water spray or deluge systems can be designed according to the international guidelines VdS 2109 or NFPA 750. CEN and CEA standards on water spray systems are in preparation. These systems are used for the protection of rooms and objects with a danger of a fast fire increase and the necessity of a huge cooling. With a discharge time of 30 minutes water spray systems are solely fire suppression but not extinguishing systems according to the guidelines. Depending on the risk a water discharge of up to 30 mm/min is prescribed. For room protection one water spray nozzle is allowed to cover 9 m^2. No specifications about the droplet diameters are given. In contrast to sprinkler systems water spray systems are released centralized.

4.2 The Siemens Solution

As discussed in section 3, the extinguishing effect of water mist systems is based on inertisation. Therefore these systems cannot be used for object protection, the same argumentation as for nitrogen, argon or HFC 227ea-systems applies here.

For the use of water-based technology in local application Siemens Building Technologies has decided to develop an advanced water spray system mainly for object protection. It has the objective not only suppress a fire, but to be able to extinguish it within one minute as reliable as a CO_2-extinguishing system does. Only in fulfilling this specification, Siemens CerSpray is suitable as water-based alternative to CO_2 for local application.

Water Amount

The following table gives the power per m^2 fire for different fire loads.

	Fire Power [kW/m^2]
Heptane	1900
Fuel/Gasoline	1900
Ethanol	1100
Plastics	900
Wood	220
Paper	730

Fire power for different fire loads

The evaporation enthalpy of water is 2256 kJ/kg. As in CerSpray no inertisation effects are taken into account, the only contribution to the extinguishing effect is the energy consumption due to evaporation in the fire zone. With the above enthalpy, the extinguishing capacity of 1 kg/m^2s water is 2256 kW.

The necessary water amount has now to be adapted to the fire risk, according to the table above including a certain safety. For fuels the value of

$$m^*_{water} = 1\ kg/m^2s = 60\ mm/min.$$

is necessary to achieve an initial extinguishing directly after start of the discharge. Allowing longer extinguishing times, the following water amount were found experimentally for fuels:

Extinguishing Time [s]	**Water amount [kg/m^{2}s]**
30	0.5
60	0.25

In any case it is necessary that the water droplets evaporate in the seat of fire and not before entering it. This has to be achieved by choosing an ideal nozzle position and droplet diameter.

Droplet Diameter

The droplet diameter is crucial for the extinguishing success of a water spray system. Too small droplets evaporate before entering the seat of the fire and have so no extinguishing effect, too large droplets have a smaller specific surface and may therefore passing the seat of a fire without fully evaporating.

The Siemens CerSpray system is a low-pressure water system with a typical nozzle pressure of 5 to 15 bar. The following graph shows the extinguishing capacity in the seat of a fire for several droplet diameters and different distances between nozzle and reaction zone. A discharge amount of 0.25 kg/s was assumed, what is equivalent to a maximum extinguishing capacity of 564 kW.

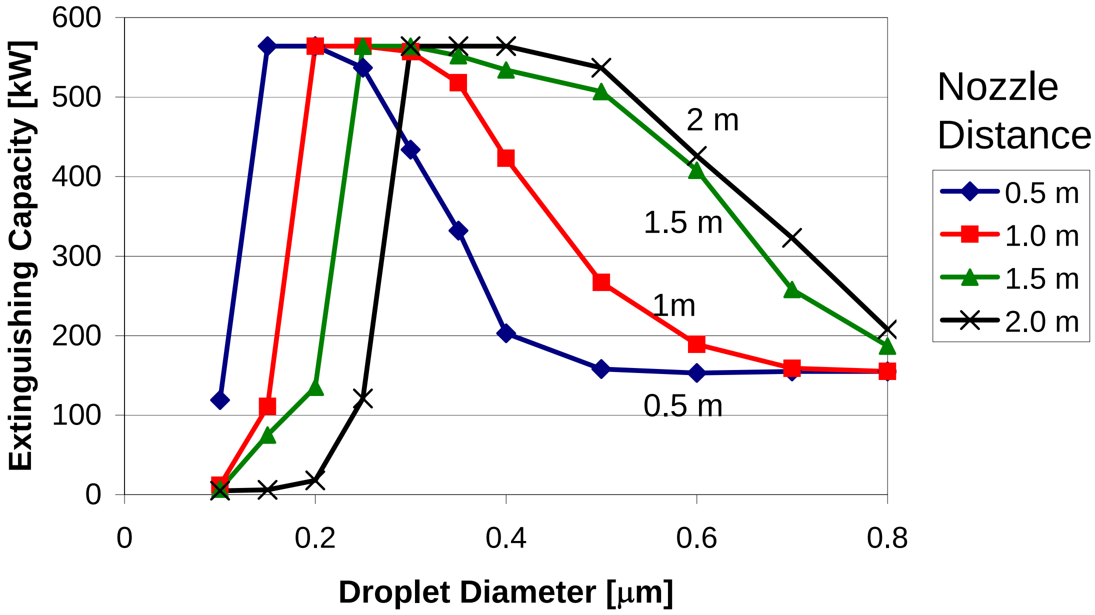


Figure 4: Extinguishing Capacity at Different Droplet Sizes and Nozzle Distances

Obviously the optimum droplet diameter and the distance of the nozzle to the seat of the fire are correlated. The following table gives the result. The adjustment of the droplet diameter can be realized by the variation of the nozzle pressure.

Nozzle Distance [m]	0.5	1.0	1.5	2.0
Droplet Diameter [μm]	200	250	300	350

The above results are calculated based on the standard equations for momentum, energy and mass transfer [5]. The droplet movement is described by the equation of conservation of momentum:

$$\frac{d\left(M_D \vec{v}_D\right)}{dt} = M_D \cdot \vec{g} - \vec{F}_R \,. \tag{7}$$

The friction force is given by (8), using the relevant relations to determine the friction factor c_w depending on the Reynolds number.

$$F_R = c_W \cdot \frac{\rho_G}{2} \cdot \pi \cdot r_D(t)^2 \cdot v_D(t)^2 \tag{8}$$

For calculating the friction force the relative droplet velocity to the surrounding gas has to be taken into account. The energy balance fro an individual droplet is:

$$Q_D^* = M_D \cdot c_{p,H20} \cdot \frac{dT_D}{dt} + m_{H20}^* \cdot \Delta h_{H20} \tag{9}$$

The heat transfer Q* to the surrounding gas is given by equation (10) and can be calculated using the correct Nusselt relation.

$$Q_D^* = \alpha \cdot 4\pi \cdot r_D(t)^2 \cdot \left(T_D - T_G\right) \tag{10}$$

The mass of a droplet is one the one side reduced by the evaporation process, on the other side coalescence or droplet break-up can occur. The mass balance has to be taken over all droplet k:

$$\frac{dM(t)}{dt} = \sum_k m_k^* \tag{11}$$

With the correct Sherwood-relation, the mass transfer for a single droplet k is resulting from 12:

$$m_k^* = \beta_k \cdot 4\pi \cdot r_k(t)^2 \cdot \frac{M_k \left(p_k - p_{k,Sat}\right)}{8.314 \cdot T} \tag{12}$$

Equations (7) to (12) allow a full modelling of the droplet behavior.

System

The system can be realized like an ordinary water spray system, using a water reservoir and a pump, or as presented in the figure, using nitrogen as propellant and storing the water unpressurized in cylinders.

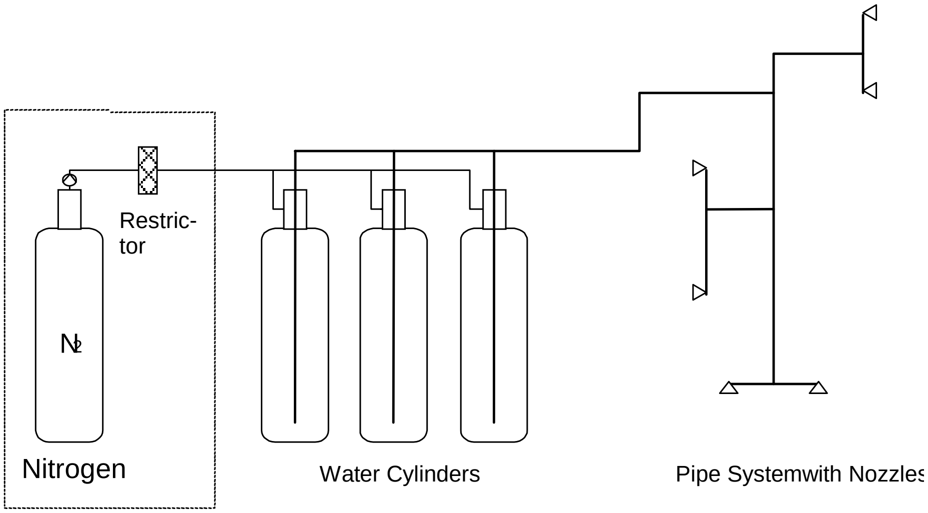


Figure 5: Principle of the Siemens CerSpray-System

The main task in designing a system is the risk dependent determination of the water amount and the realization of the correct relation between the three values

- nozzle distance (often determined by the local possibilities)
- droplet diameter
- nozzle pressure.

CerSpray has successfully passed the German VdS extinguishing tests for motor and engine protection and proven to be an alternative in extinguishing of local applications.

4.3 Tunnel Protection

A special application for water-based systems is the protection of tunnels and underground traffic systems. As in such system usually no tight enclosures can be formed, a water mist system with an extinguishing principle based on inertisation – as described in chapter 3 – can not work safely. On the other side it is also not possible to arrange a nozzle positioning, which allows a full object protection as described in chapter 4, for the sole reason, that a fire can be here located anywhere and is even possibly hidden by traffic objects (e.g. a fire under a truck or an engine fire in a vehicle). Thus the target cannot be a guaranteed full extinguishing, but a fire suppression. This suppression should protect lives by reducing the temperature below 50°C and by reducing the fire size so that no critical amount of toxic smoke gases is created. The water-based suppression system shall have a minimum discharge time, which is long enough to enable intervention forces to reach all points of the protected tunnel.

In order to design such a water-based protection system, the tools developed in chapter 4 a re extremely helpful, as they allow to calculate an optimum droplet size and the necessary water amount in order to control possible fire sizes by installing nozzles t the tunnel ceiling. Calculations have shown that an optimum droplet size for such an suppression system is in the range of 0.3 to 0.4 mm. Based on its CerSpray system Siemens Building technology has developed a protection concept for tunnels, too [6].

5 Conclusions

Water-based technologies as water mist and water spray are giving new impulse in the development of the international extinguishing market. Basic thermodynamic and physical considerations show the opportunities and drawbacks of these technologies. While 5].water sprays can guarantee extinguishing with a proper design in case of local applications, pure water mist systems for room protection are not able to offer the same degree of protection as existing gas extinguishing systems do.

Based on these results, it is possible to developed water-based extinguishing systems for both room protection and local application, which meet the standards set by gas extinguishing systems.

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