Evaporative Cooling for Protection of Tunnel Ventilation Equipment

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1 ABSTRACT

The standard requirement for exhaust tunnel ventilation fans, motors, dampers and other related mechanical equipment located in the exhaust air stream is that they have to operate in a high temperature environment during a fire emergency. However, it is not easy to upgrade this type of equipment for most old tunnels. An alternative solution is to protect the equipment using a water mist system. This paper discusses an innovative application utilizing an old approach supported by engineering calculations, CFD analysis and available test results. It shows its feasibility, advantages and disadvantages. It focuses on the ability of evaporative cooling to drop the temperature of hot gases and smoke to values acceptable for tunnel ventilation equipment operation, the effectiveness of the system, as well as other issues to consider.

2 INTRODUCTION

The current NFPA 502 Standard states that all tunnel ventilation fans that are to be used during a fire emergency and exposed to elevated temperatures, their motors, and all related components, all dampers, actuators, accessories, and sound attenuators that are exposed to the exhaust air stream from the roadway fire, shall be designed to remain fully operational in an air stream temperature of 250 °C for at least 1 hour (1).

Few of the existing fan chambers built before the 1970s meet the temperature requirements of NFPA 502. Old equipment can withstand temperatures of approximately 60°C but not much higher. The following alternatives are usually considered for fire hardening of the exhaust fan equipment:

1. Replace the mechanical and electrical system components in the ventilation chambers to comply with NFPA 502 Standard temperature requirements.
2. Separate the mechanical equipment from the exhaust air stream by providing fan inlet boxes, partitions and relocating the existing motors and other mechanical/electrical equipment so that it is not affected by high temperatures.

While the first alternative seems obvious, it is often very expensive:

- Existing fans and motors could be in good working conditions and may not require immediate replacement;
- Existing fan chamber space constraints may not allow for easy replacement;
- Replacement of the V-belt drive fans with high temperature direct drive fans can result in major structural alterations;
- Replacement of V-belt drive fans with chain drive can cause noise, vibration, maintenance and reliability problems;
- Demolition of the old equipment may require special environmental assessment including lead based paint abatement and asbestos removal;
- New industry recommended heat release rates (1) may lead to higher temperature motors and additional chamber structural fire hardening;
- Ever changing requirements can result in equipment and structural upgrades/modifications;
- Mechanical equipment replacement may impact tunnel operational safety during construction activities.

The second alternative, depending on the chamber arrangement, can be a more cost effective solution. However, when the chamber arrangement does not allow for simple alterations, more complex and expensive alterations are required. Such as:

- Construction of new separating walls (fan inlet boxes) and relocation of existing structural walls;
- Heavy construction activities associated with demolition of old motor/fan pedestals and construction of new ones;
- Relocation of electrical panels and additional structural fire hardening may be required;
- If V-belt drives are used for the existing fans, the drives may require replacement with chain drives that can cause noise, vibration, maintenance and reliability problems.

Depending on the sight conditions neither of the above alternatives may be a feasible solution. In this case, cooling the entire fan chamber by means of an evaporative cooling system is a third alternative to consider. Evaporative cooling protects both the mechanical equipment and the chamber structure. This alternative:

- Does not require changes to the existing mechanical/electrical equipment;
- Requires minimum construction activities and does not impact tunnel safety during construction;
- Requires periodic testing and maintenance of the evaporative cooling system.

This paper discusses the evaporative cooling alternative, utilizing a water mist system. Our focus is on the engineering of this system.

3 TUNNEL VENTILATION EQUIPMENT TEMPERATURE REQUIREMENTS

As stated above, few of the existing fan chambers built before the 1970s meet the temperature requirements of NFPA 502. Old equipment can withstand temperatures of approximately 60°C but not much higher. This is primarily based on the limiting operational temperature of old motors and V-belt drives located in the exhaust fan chambers. For many of the older motors, the maximum motor winding temperature is in the 95°C range and the maximum temperature for motor winding insulation is in the 105°C range. The fan belts can operate safely in an environment up to about 65 °C. There are uncertainties in the consideration of the maximum allowable operating temperature of the motors and V-belts. Therefore, 60 °C temperature can be used as a conservative maximum operating temperature for old fan systems that employ V-Belt drives.

4 EVAPORATIVE COOLING AND WATER MIST SYSTEM BASICS

Direct evaporative cooling has been well known in the HVAC industry for a century as an effective and simple method of reducing air temperature. With direct evaporative cooling, air is blown through a water-saturated medium and cooled by evaporation. The medium could be either a liquid bath or spray. A common type of evaporative cooling is an air washer. Air washers are typically used to cool and clean air, as well as to achieve significant energy savings.

Heat transfer happens between the air stream and water droplets during direct evaporation. The efficiency of evaporation depends on many factors, including surface of water droplets which are in contact with air, the due point temperature, the partial pressure and contact time. The most important property of water is its cooling capacity; in vaporization, water can absorb energy over 2 MJ/kg. Evaporative cooling is based on the latent heat of vaporization which makes it an adiabatic process. Evaporation and heat transfer are very dependent on the incoming air temperature and moisture content.

Water mist consists of a huge number of small water particles which increases the overall surface of contact between air and water. That is one of the reasons we consider water mist systems suitable for applications where large volumes of air require significant temperature drop within a short period of time. Another reason to consider a water mist system is that the fog it creates is somewhat homogeneous and safe for most electrical equipment applications.

The high-pressure water mist system was developed to produce “fine” water spray, (i.e. small droplets at higher discharge velocity) by utilizing pumps, pipes and nozzles. The pressure at the water mist nozzles can vary from 7,000,000 to 10,000,000 Pascal, with droplet sizes typically from 50 to 100 microns in diameter. This is equivalent to a total surface area of 300 to 400 times larger than the surface area provided by the droplets of a conventional sprinkler. Large surface area for heat transfer, superior heat absorption, efficient deep penetration and rapid cooling are achieved due to small high velocity droplets discharged by a high-pressure water mist system. This has been demonstrated through many tests conducted at laboratory-scale and in the field.

5 METHODS OF CALCULATIONS

A water mist system includes pipes, valves, nozzles, a control panel, and a pump assembly. Pumps distribute water through pipes to water mist nozzles in an exhaust fan chamber. The mist should cover incoming air in the exhaust chamber and provide maximum contact time while avoiding condensation.

The approach for each exhaust fan chamber is as follows:

- First, determine the water flow requirements for each exhaust fan chamber;

- Second, estimate the total water flow/pump requirement based on the fire emergency ventilation;
- Third, using the design total water flow rate, re-evaluate the cooling of each exhaust chamber; and
- Finally, conduct three-dimensional flow simulation using computational fluid dynamics (CFD) to confirm the performance of the designed water mist system.

The following sub-sections discuss the calculation methodology and the equations used to calculate water flow requirements and resultant exhaust chamber air temperature.

5.1 HI-FOG Methodology

Marioff (2) has suggested a methodology to find out:

- How much water flow is necessary to cool a certain amount of hot air down to a specified temperature level;
- How the specified temperature can be achieved with water mist cooling.

It is assumed that the air flow has a fixed volume. The water mist nozzles are located within the air flow, allowing the water mist to mix well with the air. It is also assumed that the mixing is perfect so that the system is homogeneous, and that the cooling of the hot air is fast enough so that when the mixture exits the cooling system everything is at uniform temperature. Furthermore, it is assumed that the incoming air is dry and the outgoing air either has 100% relative humidity (saturated) or, at the least, all the water has been evaporated. It should be noted that these assumptions are critical and require verification.

The droplet size is essential when it comes to the cooling time, since small droplets will evaporate faster. The amount of water required to reach the maximum cooling is proportional to the air flow rate and the initial air temperature (conditions). Marioff provides two examples of cooling air from 315°C and 430°C with 15°C and 20°C water and concludes that it is practically impossible to cool the airflow to 50°C. However, in both cases, the final temperature of 60°C was achieved, which is acceptable for protection of equipment.

In general, about **<u>0.5 ml of water is needed to cool 1 m^3 of air by 1°C</u>**, regardless of the initial temperature. The cooling power of evaporating water is about 38 kW per 1 l/min of water flow.

Marioff (2) provides the curve which shows the relationship between initial and final temperatures (Fig. 1). Using the graph, one can determine how low a temperature can be achieved by water mist evaporative cooling. For example, if the initial gas temperature is 315°C, cooling down to about 60°C is possible. Airflow at 250°C can be cooled to 55°C. This approach neglects any heat loss to the surroundings; in real life cooling below the limiting temperature can occur.

Marioff concludes that **<u>1 l/min of water mist is capable of cooling 40 m^3/s of air by 1°C</u>**. The cooling effect of the water will stop when the final temperature (Fig. 1) is reached regardless of increasing the water flow.

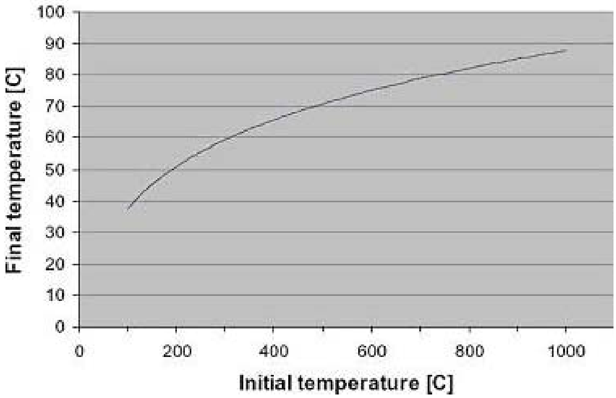

Figure 1. The final gas temperature vs. the initial gas temperature, assuming sufficient amount of water mist is applied.

5.2 Energy Balance methodology

Preliminary calculations are used to evaluate the water flow rate so that the pump size can be determined. These calculations are based on energy balance, which assumes homogenous mixing of the water mist with the hot air. The basic equations used are described below followed by an outline of the calculation procedures.

5.2.1 General equations of energy balance for water / air mixing

Equation 1 describes the mixing of the air stream with the water mist. It is assumed that a fraction of the water will be evaporated to saturate the air stream. This fraction can be obtained from the saturation humidity ratio in Equation 2.

$$m_w h_w + m_a h_a = \left(m_a h_{oa} + m_w f h_{ow}\right) + m_w f h_{fg} + m_w \left(1 - f\right) h_{owl} \quad \textbf{Equation 1}$$

$$f = \frac{w_{sat} m_a}{m_w} \quad \textbf{Equation 2}$$

Where,

- m_w – mass flow rate of water;
- m_a – mass flow rate of air;
- h_w – enthalpy of water before mixing;
- h_a – enthalpy of air before mixing;
- h_{ow} – enthalpy of water vapor after mixing;
- h_{oa} – enthalpy of air after mixing;
- h_{fg} – change of enthalpy for water evaporation;
- f – fraction of water evaporated to reach saturation;
- h_{owl} – enthalpy of water (liquid) after mixing;
- w_{sat} – saturation humidity ration.

When $f < 1$, the amount of water supplied would be excessive, resulting in partial mixing, evaporation and some of the water droplets remaining in the liquid state;

When $f \geq 1$, this means all the water mist is evaporated and Equation 1 can be simplified as shown in Equation 3. This is the assumption used for initial calculations.

$$m_w h_w + m_a h_a = \left(m_a h_{oa} + m_w h_{ow}\right) + m_w h_{fg}$$ **Equation 3**

As the air mixes with the water vapor and passes through the mist, the mixture volume must satisfy the fan law. The combined volume must be equal to the constant fan volume flow rate. This can be evaluated from the mass continuity using density of each mixture component. The density of the mixture is mass-weighted based on the density and the mass of air and water vapor (Equation 4).

$$\rho_{mix} = \left(\frac{m_a}{m_a + fm_w}\right)\rho_a + \left(\frac{fm_w}{m_a + fm_w}\right)\rho_w$$ **Equation 4**

The constraint is that the volume flow rate of the mixture must equal the exhaust rate of the fan, that is,

$$V_{mix} = \frac{m_a + fm_w}{\rho_{mix}} = V_{fan}$$ **Equation 5**

5.2.2 Calculation procedures for water flow requirement

Given that the incoming air temperature is at 250°C and that after mixing with the water mist the air/vapor mixture temperature is 60°C, the water flow rate can be calculated, assuming 100% evaporation and complete mixing as follows:

1. Determine the enthalpy properties of vapor and air at 60°C;
2. Assume and later adjust the mass flow rate of air coming to the chamber, m_a;
3. From Equation 3, calculate the mass flow rate of water, m_w;
4. Determine, from Equation 5 ($f = 1$), the volume flow rate of the mixture, V_{mix};
5. If V_{mix} equals the fan exhaust rate, STOP; otherwise repeat steps 2-5 by adjusting a mass flow rate.

5.2.3 Estimate of chamber temperature with water mist

Saturation may happen when the amount of water mist supplied is more than is needed to cool the air stream. When saturation occurs, cooling below the saturation temperature (dew point) would not be possible and the water mist is only partially evaporated. The air stream will be a mixture of water vapor, air and water mist. The calculation is then:

1. Set a mass flow rate for water mist, m_w;
2. Assume and later adjust a mixture temperature (temperature of air, vapor and water droplets);
3. Determine the enthalpy properties of liquid water droplet, vapor and air;
4. Determine the fraction of water evaporated to saturate the air (Equation 2);
5. Calculate, from Equation 1, the mass flow rate of air, m_a;
6. Determine, from Equation 5, the volume flow rate of the mixture of vapor and air, V_{mix};
7. If V_{mix} equals the fan exhaust rate, STOP; otherwise repeat steps 2-7 by adjusting mixture temperature.

5.2.4 CFD verification

CFD is disused in section 7.3. While physics is well established, the processes that happen, such as water evaporation, are quite complicated. Very limited verifications of

CFD results against field tests are available (6, 7, 8, 9, 10). Complicated aerodynamics inside the exhaust chambers is another complexity factor. This creates scepticism in reliability of CFD results. However, analysis allows for the determining of major trends in evaporative cooling using water mist technology.

6 WATER MIST SYSTEM CONTROL CONCEPT

A water mist system employs open nozzle heads with water being discharged after opening a control valve in the exhaust fan chamber. The valve is activated by an automatic detection system or a manual control valve and/or by an override from the control panel.

When a small fire occurs in the tunnel, it is likely that the air stream temperature may not reach 60°C in the exhaust duct. The use of a heat detector at the exhaust fan chamber is to ensure that the water mist system only operates when the air temperature exceeds 57°C.

The motor and pumps for the water mist system will start after the activation of the emergency ventilation fans. The control valve is activated after the exhaust duct air temperature is detected higher than 57°C and the dampers are in the open position. The operational sequence for a typical exhaust fan chamber is described below (Figure 2):

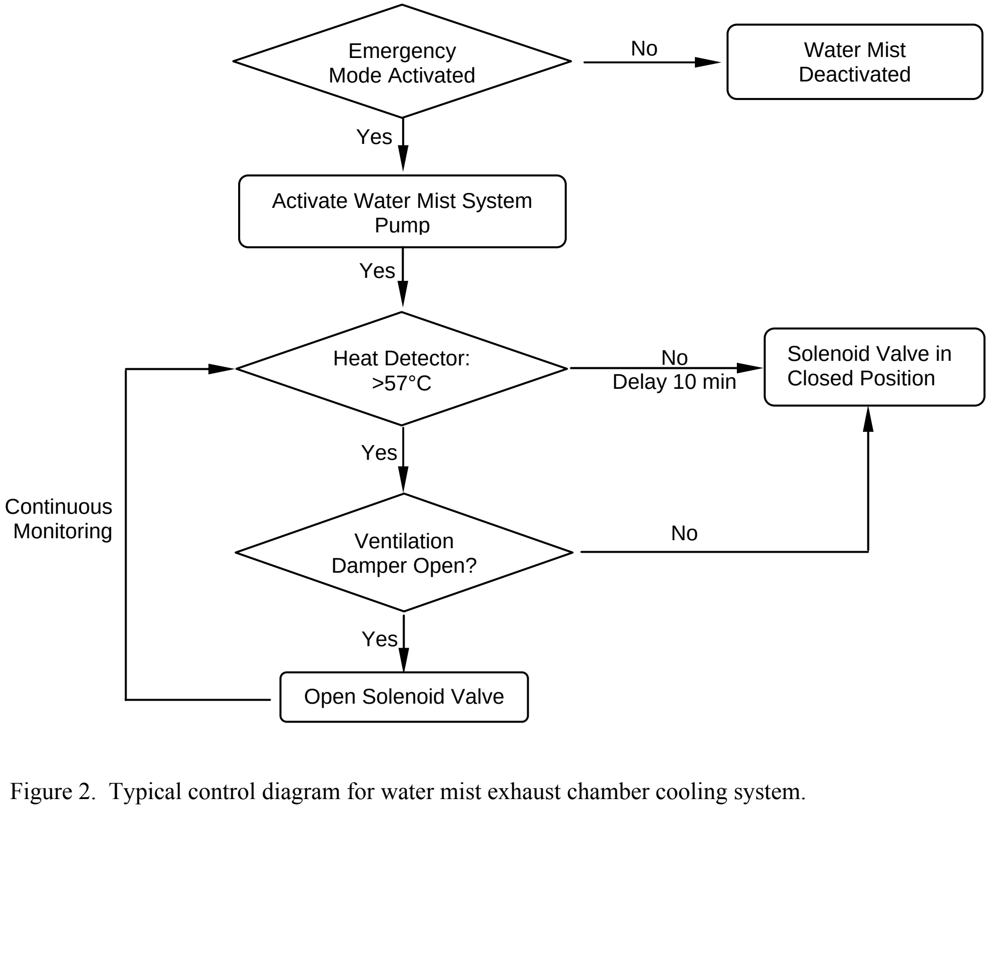

Figure 2. Typical control diagram for water mist exhaust chamber cooling system.

1. Fire is detected in the tunnel, emergency ventilation fan(s) starts and damper(s) open;
2. The emergency signal starts the pumps for the water mist system;
3. The solenoid valve opens and water discharges when the exhaust air temperature reaches 57°C and dampers are in the open position;
4. When either the air temperature goes below 57°C or the damper returns to the closed position, the solenoid valve closes. A time delay can be used before closing the valve;
5. Once the emergency ventilation mode is deactivated, the pumps are stopped.

In our example the heat detector is positioned in the exhaust air duct, upstream of the damper opening, to monitor the temperature of the air stream coming to the exhaust fan chamber.

The control system can be modified to minimize the water discharge for small fires, as well as to account for fire growth and decay time. This allows for the activation of the required number of nozzles based on incoming air temperature and humidity. Variable K-factor nozzles are required for such application.

The following example shows usage of multiple nozzles (or sets of nozzles). This system control concept is presented on the psychrometric chart (Fig. 3). This chart shows evaporative cooling based on an individual nozzle activation control system:

- When the exhaust air temperature reaches 57°C, the first nozzle(s) activates and cools the chamber to 32°C (saturation point). As the fire grows, the exhaust air temperature rises and the relative humidity of the chamber air drops to 30%.
- When exhaust air temperature reaches 88°C, the second nozzle(s) activates and cools the chamber to 36°C (saturation point). As the fire grows, the exhaust air temperature rises and the relative humidity of the chamber air drops to 40%.
- When exhaust air temperature reaches 120°C, the next nozzle(s) activates and cools the chamber to 40°C (saturation point). As the fire grows, the exhaust air temperature rises and the relative humidity of the chamber air drops to 50%.
- When exhaust air temperature reaches 180°C, the next set of nozzle(s) activates and cools the chamber to 46°C (saturation point). As the fire grows, the exhaust air temperature rises and the relative humidity of the chamber air drops to 65%;
- The last nozzle in this example can be activated when the exhaust air temperature reaches 250°C. The chamber air is cooled to below 60°C as required.

The control points are adjusted for each chamber to the specific chamber conditions.

The conditions in the chamber are transient. The points shown on the chart are the points that the system passes through but seldom ever stays at. The lines between the points represent air changing conditions.

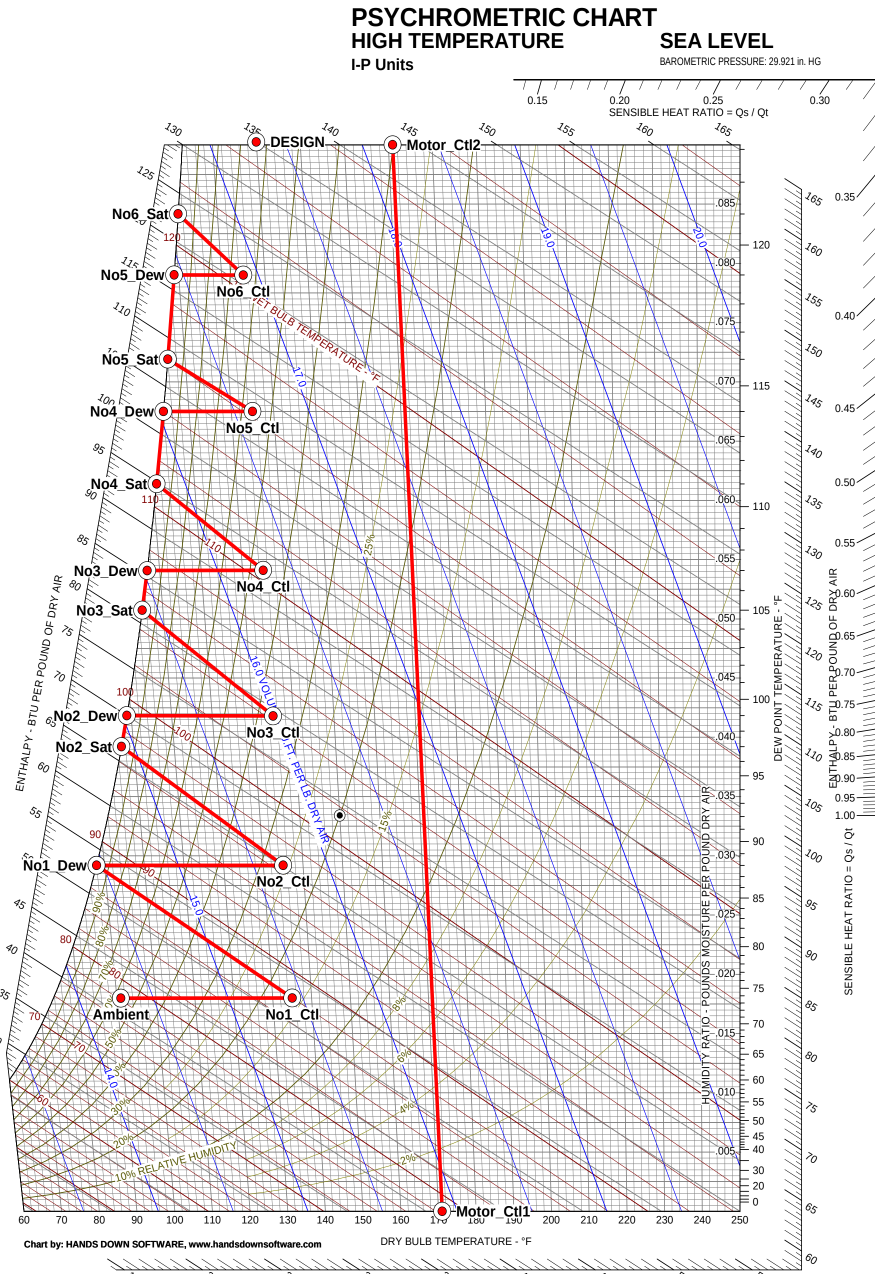

Figure 3. Psychrometric Chart for exhaust chamber evaporative cooling based on individual nozzle activation control system.

7 EFFECIENCY OF EVAPORATIVE COOLING

The efficiency of an evaporative cooling system is complicated and requires further research and experiments. We will address several of the many factors that will impact the efficiency. One of the methods to study system efficiency is to perform CFD analysis. However, limited field verifications of CFD results along with the complexity of the problem does not allow for full reliance on CFD.

7.1 As a function of the mist distribution system

Water mist nozzles are characterized by the depth of penetration of water mist, by the cone angle of water discharge, by K-factor and by the angle of nozzle discharge. The task is to achieve a homogeneous air/water mist mixture that covers the entire incoming airflow. Based on the depth of water jet penetration and cone angle, the required number of nozzles can be obtained along with their best possible locations (Figure 4).

The air flow pattern and the localized mixing / cooling by the water mist are affected by the nozzle locations and by the nozzle angle. CFD analysis is a tool for further investigation of these factors.

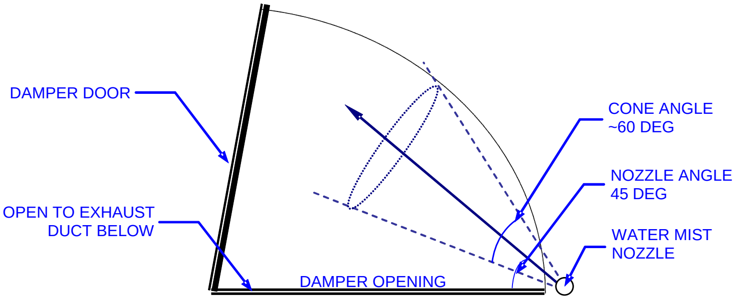

Figure 4. Inlet duct opening and angle of water mist nozzle supply.

7.2 Time it takes for a droplet to evaporate

Newton’s law of forced air convection could be used for evaluation of time it takes for a water droplet to evaporate in a turbulent air flow:

$$Q = h\ a\ dT \qquad \text{Equation 6}$$

Where,

Q – heat transfer rate;
h – heat transfer coefficient;
a – area;
dT – temperature difference

The complexity is in the evaluation of the overall heat transfer coefficient, i.e. the coefficient of forced convection of turbulent water flow drops in turbulent airflow. For natural convection, water film coefficients are in the range of 4500 to 11300 W/m^2 K. Typical values of overall coefficients of heat transfer between cold water and hot air could also be found in literature (4), but depend on the type of heat exchanger. Further investigations are required for accurate evaluation of the heat transfer coefficient for the application of water mist in the exhaust chamber.

Once the heat transfer coefficient is established, the time it takes for a droplet to evaporate can be calculated as follows:

1) The amount of heat to be removed by water mist is calculated based on the airflow rate in the chamber and temperature difference between entering air temperature from the tunnel and acceptable air temperature for mechanical equipment;
2) Calculate the number of water droplets discharged by the water mist system per unit time by dividing the water volume flow rate by volume of a water mist droplet;
3) Knowing droplet trajectory, calculate the amount of time a droplet stays in the chamber;
4) Calculate the amount of heat exchanged at equilibrium between air and one droplet using Equation 6 and knowing mist droplet surface area;
5) Find the time it takes all the droplets (water flow) to reach equilibrium using Equation 6.

Equations are based on constant surface areas and constant vapour pressures. However, the mist droplet area varies from 50 microns to 150 microns and decreases as it evaporates. Water vapour pressure changes with temperature while the process progresses. Therefore, the above methodology can provide estimated evaporation time, but requires field verification.

Equation 6 and the methodology given above shows that fine water mist droplets allow for significant reduction in the required time for evaporation. Although this makes the system effective, complete evaporation can not happen instantaneously.

7.3 CFD Analysis

Computational fluid dynamics (CFD) provides three-dimensional (3D) solutions of fluid flow, heat and mass transfer and associated species transport. Here, CFD is used to analyze, in much more detail, the application of water mist in the exhaust chamber (Figure 5). This is to confirm the performance of the designed water mist system as well as to evaluate, through parametric studies, the sensitivity of certain water mist design parameters.

The CFD program, Fluent (v6.2), is used for this analysis (3). Fluent is a general purpose CFD program that is capable of taking into account the interaction of the water droplets and the air flow. The Discrete Phase Model (DPM) is used for tracking and modelling water droplets generated by the water mist system. This model has been previously used to evaluate the performance of sprinkler systems (6).

DPM is available in the Fluent program (3). The model considers the water mist as liquid droplets. By tracking the droplets in the flow and the interaction of the discrete phase with the gas phase, it provides:

- Droplet position tracking within the model;

- Aerodynamics drag on the liquid droplets and the force on the gas phase;
- Heat transfer between the gas phase and the liquid droplets, that is, heating/cooling;
- Heat transfer and mass loss due to droplet evaporation; and
- Heat transfer and mass loss due to droplet boiling.

The example in Figure 6 shows the water mist modelling in an exhaust chamber. Results of the CFD analysis proved the complexity of the evaporative cooling process in the chamber and allowed for nozzles to be optimized. A completely homogeneous mixture was not achieved with the CFD analysis, as assumed in the calculations and temperature differences noted in the chamber (Figure 6).

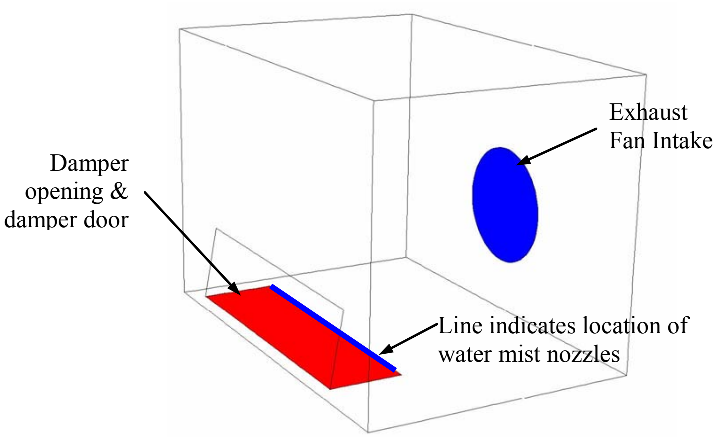

Figure 5 Simplified CFD Model of exhaust fan chamber.

Results of CFD Analysis help to better understand the processes that happen inside the fan chamber (Figure 6):

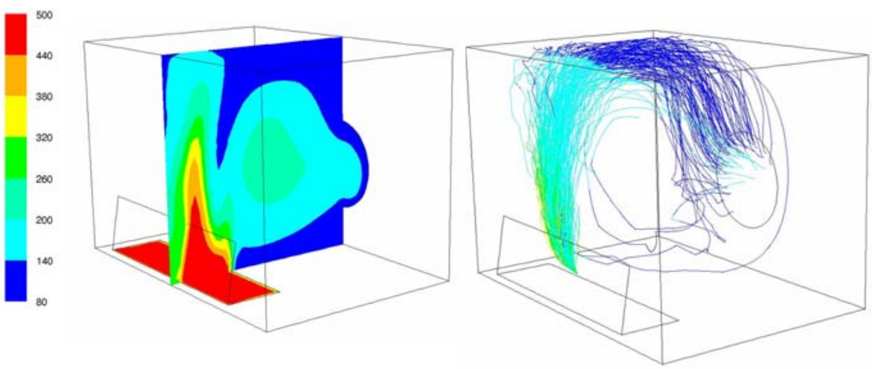

Figure 6. CFD Analysis Results – Air Temperature and Water Mist Particles Trajectory.

In summary, these results suggest that at the operating condition in the example (exhaust flow rate, inlet temperature), the water mist provides sufficient cooling to reduce the temperature of the air stream from 250°C to an average of 65°C. Although this is slightly higher than the specified 60°C, this is marginally acceptable given that the mechanical equipment can withstand those temperatures. Testing is required for verification.

8 ADVANTAGES AND DISADVANTAGES OF THE EVAPORATIVE COOLING FOR PROTECTION OF EQUIPMENT

The main advantage of the application of evaporative cooling using a water mist system for protection of tunnel ventilation equipment is the simplicity of its application. It does not require major construction activities associated with tunnel ventilation equipment replacement or rehabilitation. Evaporative cooling also eliminates the need for structural fire hardening.

Figure 7 shows average fan inlet temperatures with and without a water mist cooling system during fire emergency. The maximum air temperature without the evaporative cooling is 250°C at the fan inlet. With the water mist system, the average fan inlet temperature will not exceed 65°C. The fan will not see the maximum temperature for more than 4 minutes.

The disadvantage of this system is that it requires a significant amount of water to be discharged in the vent chambers. A complex control may be required to avoid excessive water supply into the chambers. System efficiency and optimization may require additional studies and full scale tests. System testing and maintenance is required.

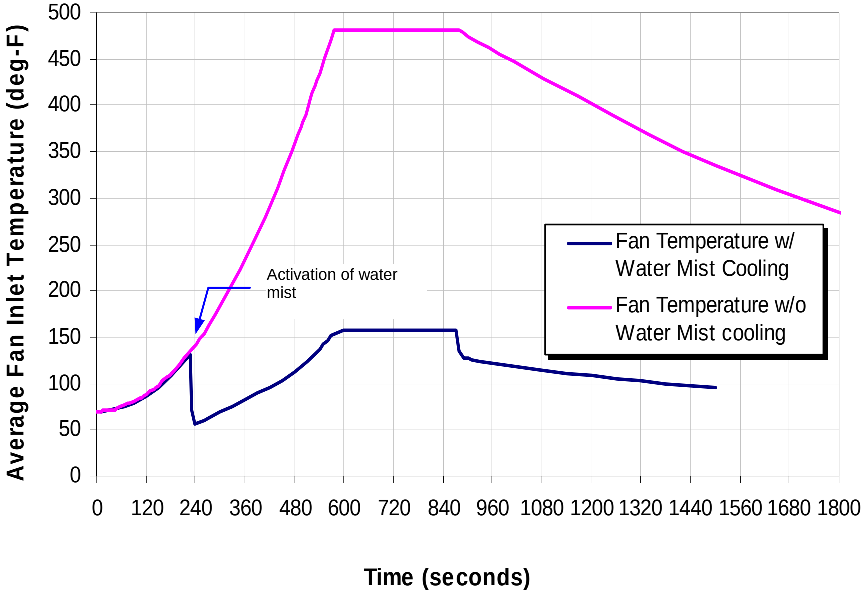

Figure 7. Resultant effect of evaporative cooling with water mist on air temperature reduction in exhaust chamber.

9 SYSTEM TESTING AND REQUIRED FUTHER INVESTIGATIONS

Water mist manufacturers have performed a series of field tests and experiments that prove the ability of fine water mist to cool high temperature gases (Figure 8). Most of the tests were performed to prove the system's ability to suppress the fire or bring it under control. With the water mist system activated, people were able to get close to the fire site because the temperature was dropped. FOGTEC Company distributed a video which demonstrates suppression of a gas flame with simultaneous cooling effect on the valve to a point that a fire fighter was able to close the valve of a burning gas tank (Fig.8). However, we believe that further system testing and investigations are still required.

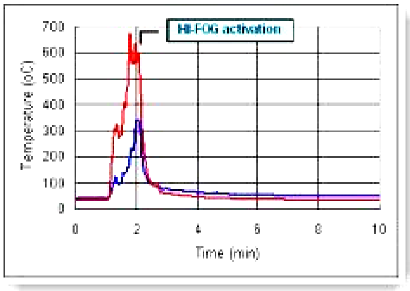

Figure 8. Cooling effect of water mist system test results (left: Tunnel fire test by Marioff; right: FOGTEC gas cooling test).

Without further system testing, it is difficult to demonstrate that the water mist will achieve complete or close to complete mixing and full water evaporation before impacting the mechanical equipment.

Additional testing is required to demonstrate how well the water mist mixes with the air since the mixing may not be perfect, the system is not completely homogeneous, the cooling of the hot air may not be fast enough for the equipment survival, and the temperature in the chamber is not uniform. Experiments and field testing are required to verify the efficiency of the system so that optimum nozzle locations and water requirements can be verified. Testing is required to show that the mechanical tunnel ventilation equipment will operate through the designed fire emergency condition.

10 CONCLUSIONS

Evaporative cooling system using water mist could be a cost effective solution for bringing the tunnel ventilation equipment in compliance with temperature requirements set by NFPA 502. Additional experimental studies and field tests are required.

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