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Fire Protection of Steel Structures by Low Pressure Water Mist in Large-Scale Fire Test

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Abstract. Water mist extinguishing systems are becoming more popular due to their much higher fire-fighting efficiency at lower water consumption compared to conventional sprinklers. The article focuses on the possibility of further utilization in a form of cooling structures and presents the results of a research in the area of low-pressure water mist and the development of a new low-pressure water mist cooling system. It also introduces a new possible direction for application of cooling steel structures or their surroundings in order to increase fire resistance of steel structures. To verify the cooling effects of low-pressure water mist, a large-scale fire test with a model of steel roof construction was carried out in a room with dimensions of 4.0 × 4.0 × 2.0 m. The fire test was conducted in two scenarios. The first scenario is a reference test without application of water mist, where temperatures of the burning room and steel structures are monitored. Compared to the first scenario, the second scenario includes the use of low-pressure water mist protection of the steel structure model at the time of full fire development.

1. Introduction

Unprotected steel structures usually reach fire resistance up to 15 minutes, exceptionally 30 minutes. The vast majority of steel elements do not meet the required fire resistance and lose their load-bearing capacity and stability when the so-called critical steel temperature is reached and the collapse of the structure is expected. Then the required fire resistance of steel structures must be ensured by passive fire protection (paint, spraying, lining, etc.) against heating to the critical temperature. In the framework of this research project the low pressure water mist is investigated as another possible method of fire protection of steel structures.

For simplification of the assessment of fire resistance of steel elements, the conservative values of critical temperatures are specified in ČSN 73 0810 [1]. For example, critical steel temperature of 500 °C can be considered for the main supporting structures such as columns, beams and trusses. Alternatively, the critical temperature can be calculated with the knowledge of specific boundary conditions of the steel element (cross-section, degree of utilization, etc.) according to EN 1993-1-2 Eurocode 3 [2]. Depending on the coefficient of cross-section and the critical temperature, the final fire resistance of the considered structure can be determined in the diagram in the **Figure 1**. Steel properties at high temperatures are determined by reduction coefficients from steel properties at normal temperature (20 °C) by reduction of yield stress and steel modulus. For a more specific idea, fire resistance requirement of 15 minutes (for profiles exposed to fire on all four sides) is satisfied by rolled steel profiles with a cross-sectional area $A_m / V < 100\ m^{-1}$ (e.g. I 450, HEB 400 or HEA 700).

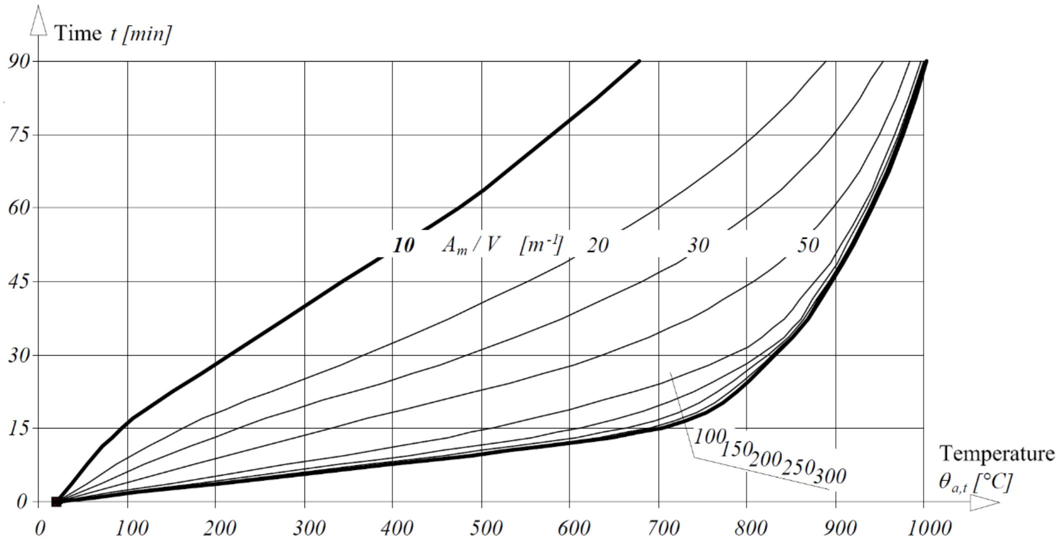

Figure 1. The dependence of the temperature of the steel unprotected profile (θa,t) on the duration of the fire (t) and the cross-sectional coefficient (Am/V) [3].

The topic of protection of steel structures (skeletons of administrative buildings, frame construction of halls, etc.) by a fire-retardant coating becomes a highly current and serious problem caused mainly its limited lifetime, usually only about 10 years. Restoration of the coating system usually requires interruption or significant limitation of operation, disassembly of number of technical equipment attached to steel structures, mechanical cleaning of the original coating and application of a new system coating. In many cases it can be very complicated or almost impossible. An alternative solution may be an extension of the existing sprinkler extinguishing system by low pressure water mist extinguishing system installed in the space of the load-bearing steel structure. It is to cool down the environment around the structures below the critical temperature during a fire situation. On the cooling system will be undertaken an annual review along with existing sprinklers and the costly overall refurbishment of the fireproof coating is no longer needed. The building becomes more sustainable and efficient.

The properties of water mist device compared to conventional sprinkler are described to details in several publications [3], [4] and diploma theses [5], [6], [7]. Low pressure water mist consists of a wide fraction of water droplets containing both heavy and lightweight water droplets. Heavy droplets have sufficient momentum to penetrate into fire and wet the burning fuel. On the contrary, light droplets with low magnitude and high quantity remain in the air and reduce heat radiation and temperature of hot surrounding gases.

It was necessary to verify the expected high cooling effects of water mist extinguishing system in case of fire situation on a large-scale experimental fire test. In the case of a low pressure water mist device it is mainly the verification of environment cooling effect and emissivity reduction in the cloud of water mist being carried out. Low pressure water mist systems with a wide spectrum of water droplet fractions create a stable spray area against the flowing gases and combine the effect of cooling the environment around the construction and wetting the structure.

No EU standard for cooling of building structures with a water mist is currently available, there is only a standard for water mist extinguishing ČSN P CEN/TS 14972 [8]. A similar experiment of protection of steel structures by HI-FOG water mist systems was carried out by the manufacturer of water mist nozzles Marioff Corporation [9]. The experiment verifies and describes a high pressure water mist cooling effects on the environment. A gas burner was used as the heat source, but the environment didn't reach temperatures of the large-scale experimental fire test according to the ISO 834 temperature curve.

2. Experimental assembly for large-scale fire test

The fire test was carried out in August 2018 on an experimental area at the UCEEB CTU in Prague in a test room with inner dimensions of 4 × 4 × 2 m according to [10] used for facade testing (see **Figure 2** and **Figure 4**). The test room is made from autoclaved aerated concrete blocks with a suspended ceiling made from cement-fiber boards. The bordering constructions of the room are resistant to the high fire temperatures and violent cooling by water mist.

The fire fuel is concentrated in the front half of the room behind the window opening and it consists of 8 wooden cribs of a total weight of 400 kg. That makes a room with fire on one half and with hot gases in the other half of the room, both with temperatures corresponding to the nominal standard temperature curve [10]. Samples of steel plates with dimensions of 0,2 × 0,2 × 0,015 m are installed representing a model of steel structure (or certain parts of the structure) in both halves of the room to measure temperatures in the structure and in the surroundings around the structure. Gas temperatures near the steel plates and temperatures inside the steel plates are measured with 3 mm diameter K-type thermocouples.

Each thermocouple in the environment around the steel plates is equipped with a cover to prevent its measuring end from direct wetting by water mist (see Figure 3). Without this precaution the measured temperatures would be compromised by water and the results would not represent temperatures of the environment. The protection by water mist is provided only to steel plates at the back of the room by two spray nozzles located on one of the side walls at the back of the room (area without fire fuel, see **Figure 3**). The spray direction is horizontal and parallel to the rear and front walls of the room.

Figure 2. View into the test room.

Figure 3. Water mist protection of steel plates.

The protection by water mist is applied only at the back of the room and not in the front of the room in order to minimalize effect of water mist on the burning fire.

Table 1. Spray specification of the water mist nozzle.

operation pressure	10 bar
K factor	2,15
median diameter	60 μm
flow rate	7,12 l/min
jet stream type	conical
latitude angle	0° to 30 °

The water mist protection begins after 15 minutes from the start of the fire test at temperatures of about 680 °C (measured at the back of the room). The protection of steel plates by low-pressure

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water mist is applied in order to reduce the environment temperature and therefore prevent the steel plates from heating to the critical steel temperature of 500 °C.

A reference (comparative) fire test with identical fire load, but without the water mist protection, is performed in order to determine the drop of temperature of the protected environment compared to the unprotected environment.

Figure 4. Test room at the 15th minute before the water mist being applied.

Figure 5. Test room at the 25th minute just before the end of protection.

3. Reference fire test without cooling

The reference fire test is used to determine the flow of the room temperature without any kind of cooling.

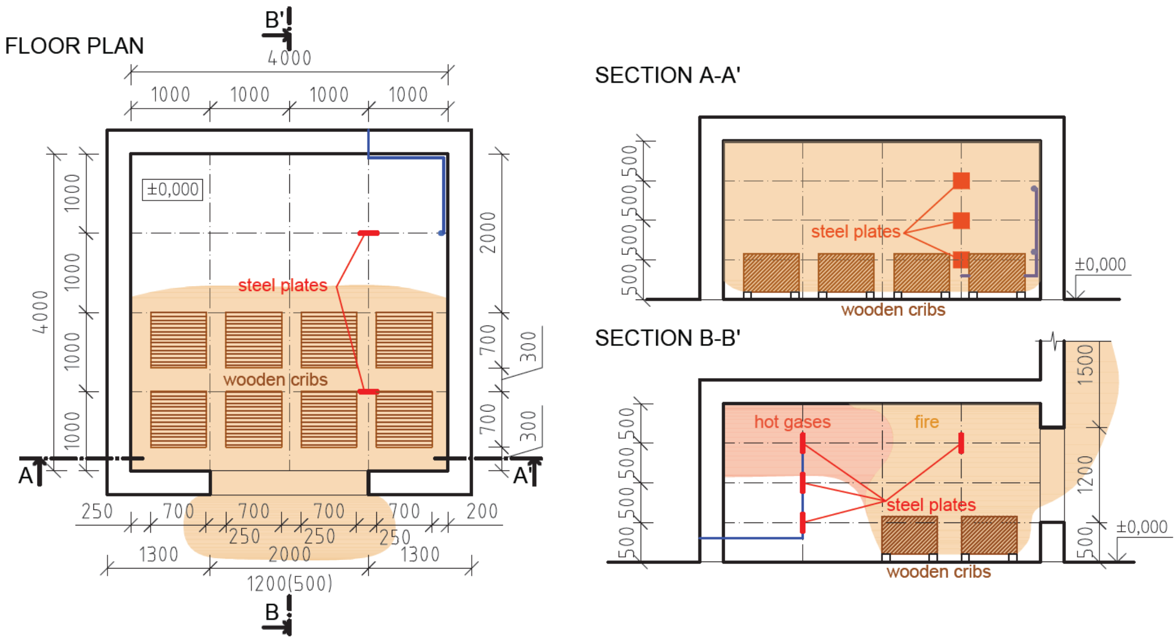

Figure 6. Experimental reference fire test assembly (without cooling).

The fire is ignited in the front half of the room. Temperatures are monitored around steel plates (see **Figure 6**) in the front of the room in the fire and at the back of the room out of the fire.

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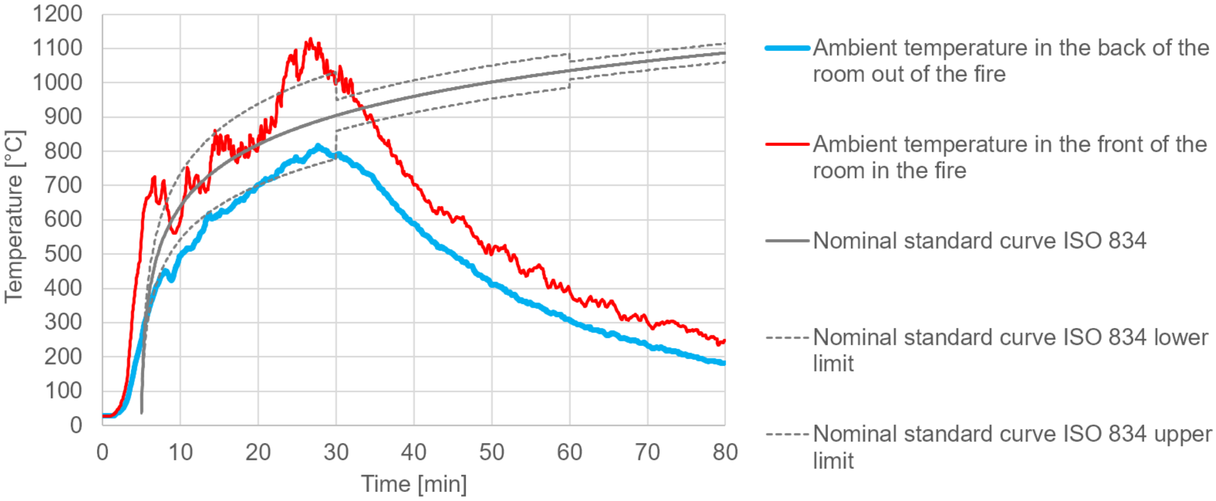

Figure 7. Ambient temperature of the room during the reference test (without cooling).

A nominal standard temperature curve (ISO 384) with a tolerance of ČSN EN 1363-1 [11] is indicated in the graph (see **Figure 7**). Temperatures measured throughout the room during the fire test correspond to the nominal standard temperature for testing fire resistance of structures.

4. Fire test with cooling

Temperatures of the environment around the steel plates in the protected area at the back of the room and in the unprotected fire area in the front of the room are monitored during the fire test. This is done in order to confirm the fact, that the environment temperature drops only in the protected area and the nominal standard temperature remains in the unprotected area.

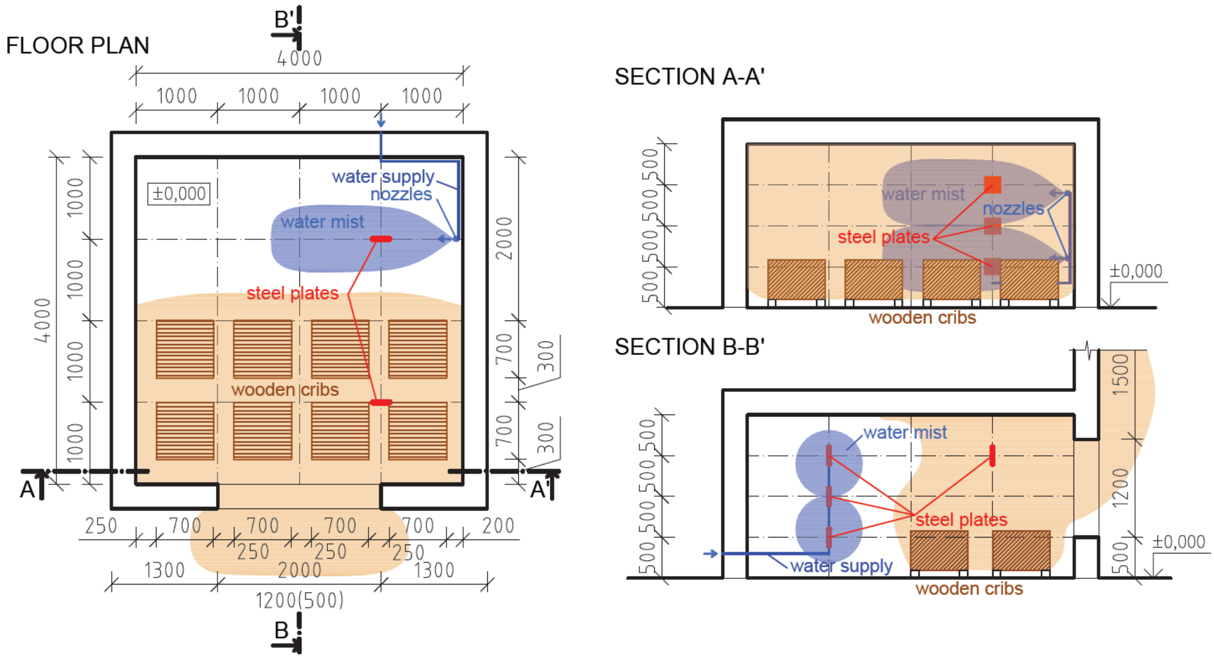

Figure 8. Experimental fire test assembly with cooling.

The cooling begins after 15 minutes from the start of the fire test and is active for next 10 minutes. Thermocouples are equipped with a water mist cover to prevent the measurement of ambient temperatures (see **Figure 3**) from influencing the direct wetting of the thermocouples during the cooling test. In order to maintain the boundary conditions covers are also provided on the thermocouples during the reference test.

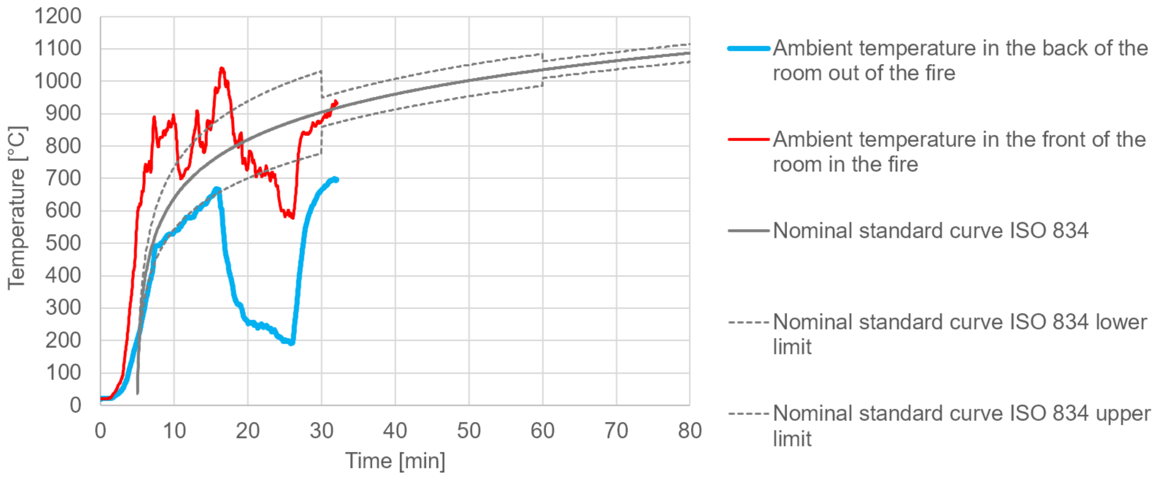

Figure 9. Ambient temperature of the room during the cooling test.

5. Comparison of reference test and cooling test

At the beginning of cooling of space around the structures, the ambient temperature in the back of the room is about 680 °C and in the fire area in the front of the room is about 1050 °C. The ambient temperature in area with applied cooling protection immediately drops down and stabilizes on about 250 °C in about 5 minutes from the start of the cooling protection. Until 8 minutes of cooling (23 minutes from the start of the test) the ambient temperature of the unprotected area (the fire) corresponds to the nominal standard temperature curve. Therefore, the experiment proves the cooling effect (not extinguishing effect) of the water mist on the ambient temperature in the protected area.

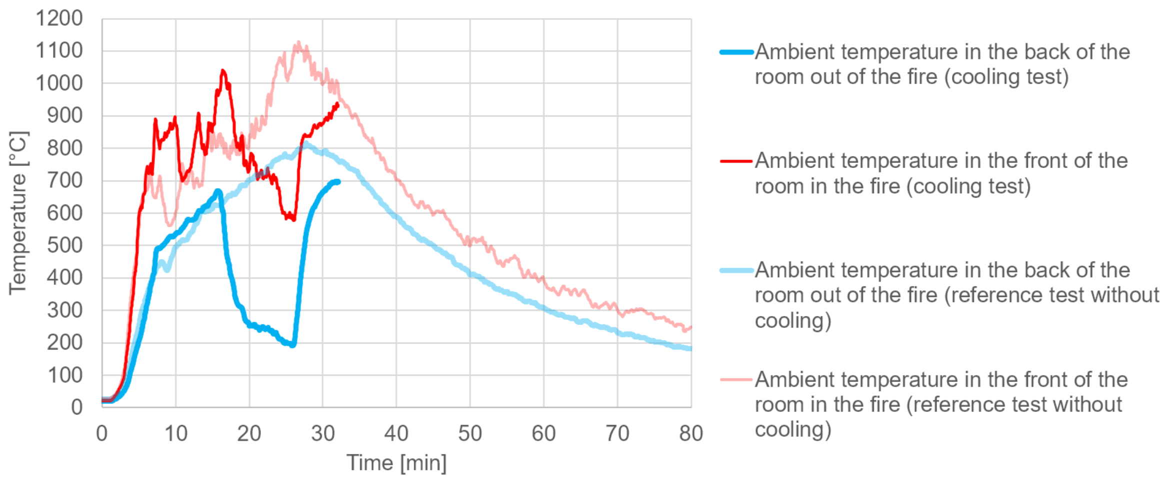

Figure 10. Ambient temperatures of the protected and unprotected areas during the cooling test and reference test without cooling.

Due to the small size of the test room in addition to high water mist efficiency the fire is partially affected during the cooling (**Figure 5**). The fire in the unprotected area is partially suppressed by a portion of the water mist that flows to the unprotected area after hitting the opposite wall and advances along the wall into the fire area causing a graduate reduction of temperature. After 8 minutes of cooling the ambient temperature in the unprotected area drops below the lower tolerance of nominal temperature curve. The standard fire conditions are not fulfilled for the last 2 minutes of cooling. The verifiable cooling effect of water mist is considered only during the first 8 minutes of cooling, where the standard fire conditions are fulfilled in the unprotected area. Despite the fire suppression the fire temperature in the unprotected area immediately returns to the nominal standard temperature of about 900 °C after the cooling process is terminated.

6. Conclusion

The experiment demonstrated the high cooling effect of a low pressure water mist system in the large-scale fire test conditions, where the ambient temperature of protected area was reduced to 250 °C, which is significantly below the critical steel temperature (500 °C). Based on the results of the experiment, water mist cooling system can be considered as effective for fire protection of steel structures. The structure will not lose the load-bearing capacity and the stability during the active water mist protection.

The water mist cooling system of steel structures provides a permanent fire protection without lifetime limitation. Application of the water mist protection solves the problem of the fireproof coating with the problematic refurbishment after its lifetime and the interruption of the service of the building.

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