The temperature development of hot dip galvanized steel members in fire

C. Gaigl & M. Mensinger

Chair of Metal Structures, Technical University of Munich, Munich, Germany

ABSTRACT

If a fire resistance rating of 30 minutes and above is required for steel constructions, a passive fire protection is needed. To optimize these cost intensive measures, one of the verification method is to determine the critical temperature according to DIN EN 1993-1-2. For this purpose, positive effects of hot dip galvanization on the temperature development of steel members for the accidental situation of fire exposure are investigated in a national funded research project in Germany. The aim is thus to avoid additional passive fire protection for a R30 requirement.

ECONOMIC RELEVANCE

The high costs of passive fire precautions, for example intumescent paints, are a huge economic disadvantage of steel and composite structures compared to simple concrete constructions. Hot dip galvanization constitutes an economic and efficient way to permanently protect steel members from corrosion. It has been used successfully for many decades, especially in the area of steel buildings and recently in steel bridge constructions.

According to Schaumann (2004), about 42% of the Germany´s office buildings have R30 requirements. The total market segment in Germany thus results in approximately 2.5 million m² per year. When hot dip galvanization additionally can contribute beneficially to the fire resistance of unprotected steel members, it would be a huge economic advantage.

FIRE BEHAVIOUR OF BUILDING COMPONENTS

Although steel and concrete are non-combustible materials, their material properties change with an increasing temperature. As early as about 100 °C are reached, the modulus of elasticity of steel starts to decrease and from about 400 °C the yield point decreases as well. Concrete loses its strength at lower temperatures, however due to steel's higher thermal conductivity, steel structures heat up much faster.

The fire behaviour of building components (e.g. walls, columns) is assessed by their fire resistance, which means that they have to maintain certain functions over a prescribed period of time in fire situation. A number of criteria are defined in DIN 13501-2. The following three criteria for load-bearing members are of interest:

- R – Load bearing capacity (The period of time that structural elements are able to carry its loadings)

- E – Integrity (The duration that the structural element retains its integrity against flames or/and hot gases in a fire)
- I – Insulation (The time it takes to engender an increase in temperature on the other side of the structural element)

HEAT TRANSPORT MECHANISMS

The exchange of thermal energy between several systems depends on their temperatures and properties of the intervening transportation medium.

Within a fire, the heat is distributed by three transport mechanisms: conduction, convection and radiation. Heat conduction depends on molecular activities and is the energy flow without particle transport, for example the heat transfer in a solid body. The second mechanism is the convection. The heat is distributed by a flow respectively a particle transport in fluids (e.g. liquids, gases). The third one is electromagnetic radiation, which is the most important mechanism for this research.

Electromagnetic radiation is the radiant energy distributed by waves of coupled electric and magnetic fields. Visible light is one type of electromagnetic radiation. Other invisible forms to the human eye are e.g. radio waves, infrared light and X-rays. Unlike, for example sound waves, electromagnetic waves do not require a medium to spread out. For instance, they propagate independently of their frequency at the speed of light through a vacuum, but within a medium, their speed slows down.

FIRE SCENARIO & ISO FIRE CURVE

The development of a fire is given in Figure 1. The horizontal axis represents the different phases of a fire whereas the vertical axis represents the temperature. At the beginning of a fire, there is the slow ignition and smouldering phase. Subsequently the full fire phase is transited, accompanied by a sudden flashover and a corresponding increase of temperature. Afterwards the cooling phase begins and the fire subsides. The intensity and duration of each phase varies strongly and depend on several influence factors like the type, quantity and distribution of the fire loads in the room, the ventilation condition as well as on the size and the thermal behaviour of the structure itself.

A nominal curve, to simplify, unify and to compare the fire behaviour of building materials and components and for representing a model of a fully developed fire in a compartment, the ISO 834 standard fire curve was introduced (Figure 1). The curve itself starts just before the full fire phase and hence the temperature raises rapidly within a few minutes, as shown in Table 1.

Table 1: Temperature development (ISO 834)

Time [min]	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Temperature [C°]	20	678	781	842	885	918	945	968	988	1006

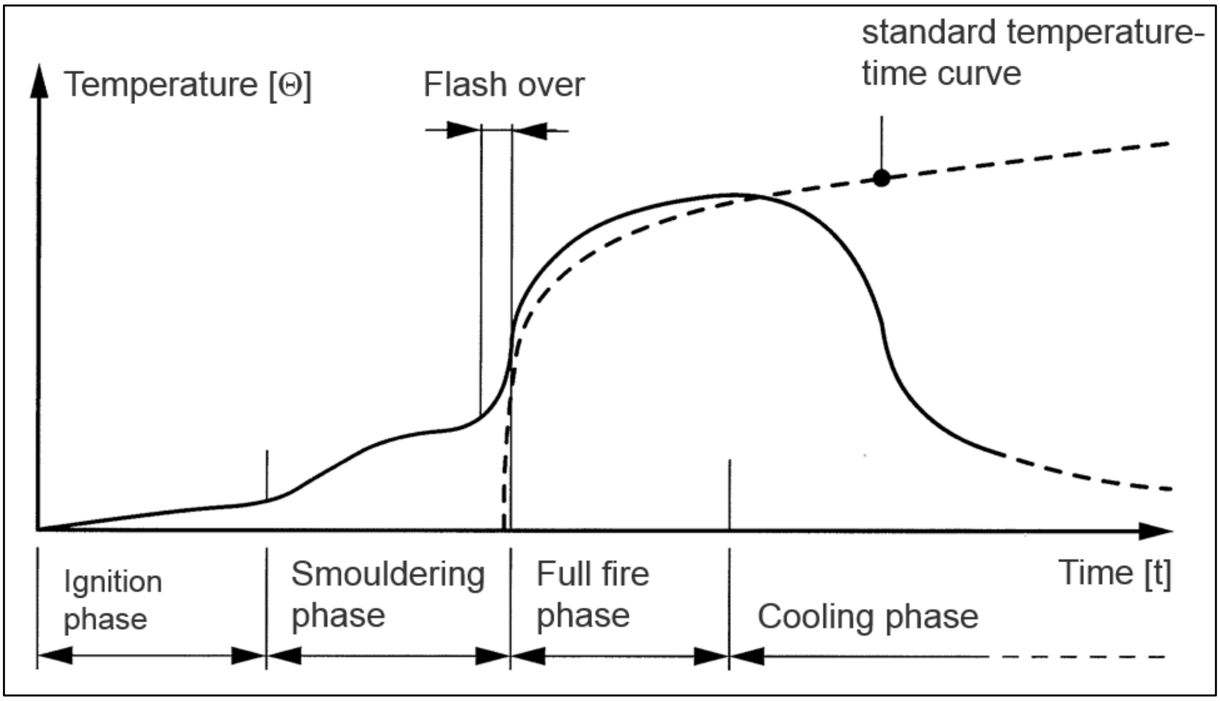

Figure 1: Typical fire progress & standard temperature-time-curve

STRUCTURAL FIRE DESIGN OF STEEL STRUCTURES ACCORDING TO EUROCODE
- SIMPLE CALCULATION MODELS -

The basis for structural design in Europe is given by the Eurocode. Thereby the Eurocodes EN 1993 - 1 - 2 and EN 1994 - 1 - 4 are dealing with the design of steel structures and steel - concrete composite structures in fire exposure. The lowest required fire criteria in Europe for load bearing capacity is a R30 (DIN EN 13501) demand. Which means that the structure has to resist 30 minutes in a fire situation.

In the different Eurocodes parts for fire exposure, three levels are available for the fire design to prove the criteria R of the load bearing capacity of a component. Thereby the second level is the simple calculation model with two different ways to prove the remaining capacity.

The first way is the design using load bearing capacity. This design format basically corresponds to the usual approach of the Eurocodes at ambient temperature. The design value of the governing loads in fire situation must be at any time not greater than the corresponding design value of capacity of the steel members in fire situation.

Alternatively, it can be shown that the steel temperature of the member does not exceed the critical temperature, which is the temperature in the member, wherein the strength or stiffness of the steel is dropped so far that the ultimate limit state is reached.

For an equivalent uniform temperature distribution in the cross-section, the increase of temperature $\Delta\theta_{a,t}$ in an unprotected steel member during a time interval Δt can be determined by following equation in the Eurocode:

$$\Delta\theta_{a,t} = k_{sh} \frac{A_m/V}{c_a \rho_a} \dot{h}_{net}\, \Delta t \tag{1}$$

with:

c_a	specific heat of steel (temperature dependent value) [J/kgK]
ρ_a	unit mass of steel: 7850 [kg/m^3]
Δt	time interval [s]; max. 5 s
k_{sh}	correction factor for the shadow effect
A_M/V	section factor for unprotected steel members [m^3]
$\dot{h}_{net}$	design value of the net heat flux per unit area [W/m^2]

On the one hand, the heating is strongly influenced by the section factor (A_M/V-value) and on the other hand by the value of the net heat flux.

As mentioned, the heating of unprotected steel members in fire depends on energy transfer by convection and radiation. These parts are represented by the net heat flux h_{net}:

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \tag{2}$$

with:

$\dot{h}_{net,c}$	Heat transfer by convection
$\dot{h}_{net,r}$	Heat transfer by radiation

$$\dot{h}_{net,c} = \alpha_c\left(\theta_g - \theta_a\right) \tag{3}$$

$$\dot{h}_{net,r} = \phi \cdot \epsilon_m \cdot \epsilon_f \cdot \sigma \cdot \left[\left(\theta_g + 273\right)^4 - (\theta_a + 273)^4\right] \tag{4}$$

with:

α_c	coefficient of heat transfer by convection
Θ_g	gas temperature in the fire compartment
Θ_a	temperature of the member surface
ϕ	is the configuration factor (depends on the angle between the radiation and the surface)
ε_f	surface emissivity of the member
ε_m	emissivity of flames, of the fire
σ	Stephan Boltzmann constant (= 5,67 × 10-8 W/m^{2}K^4)

By analysing the last two equations (3) and (4), radiation dominates the heating process due to the fourth power in case of a large difference between the gas and the steel member temperature and convection dominates the heating in case of a small one. It can be seen that the emissivity of the flames ϵ_f and more important, of the surface ϵ_m is an important variable with large influence on the radiation part of the net heat flux.

The part $\epsilon_m \cdot \epsilon_f$ of the term above is actually a simplification: The physically correct term is:

$$\dot{h}_{net,r} = \phi \cdot \left(\frac{1}{\epsilon_m} + \frac{1}{\epsilon_f} - 1\right)^{-1} \cdot \sigma \cdot \left[\left(\theta_g + 273\right)^4 - \left(\theta_a + 273\right)^4\right] \tag{5}$$

Due to the assumption in the Eurocode that $\epsilon_f = 1$, which means that the fire compartment acts like an ideal black body radiator, there is no dependence on the result following this constant. Therefore the net heat flux mainly depends on the surface's emissivity. An ideal black body is a physical idealization, as real materials emit or absorb energy at a lower level as a black body. For this reason they are called grey bodies.

TEMPERATURE DEVELOPMENT OF HOT DIP GALVANIZED STEEL MEMBERS

The heat flux from radiation highly depends on the hemispherical emissivity of construction components. The smaller the emissivity of a surface, the slower the heating develops. Galvanisation can help to improve the behaviour by influencing the heating through a smaller emissivity value of the steel member.

The bigger the difference between the temperature of the fire and the member, the larger is the influence of the emissivity (Equation 4).Therefore at the beginning of a fire the influence of the emissivity on the heating of a steel member is larger and this especially applies for members with small section factors (A_M/V-values). At later stages of a fire and in case of members with large A_M/V-values, the members are mainly heated by convection and thus the influence of the emissivity of a member's surface is of minor importance. For a member with R30 requirement and a small A_M/V-value, it is thus of interest, when a lower value of emissivity of the section surface offers some benefits to the fire design of a member.

Radiation of metal surfaces is based on atomic and molecular vibrations, depending on the chemical composition in a small layer with a thickness of about 0 to 10^{-10} m (Sala 1986). The radiation behaviour of galvanized surfaces is hence provided almost exclusively by the zinc layer itself, with a thickness of 50 to 200^{-6} m.

Emissivity depends on several surface characteristics and thereby to a decisive extent on the chemical composition, the roughness and as well on the degree of oxidization. Furthermore it is a variable depending on the temperature. With respect to this, different galvanized surfaces (e.g. category A, B

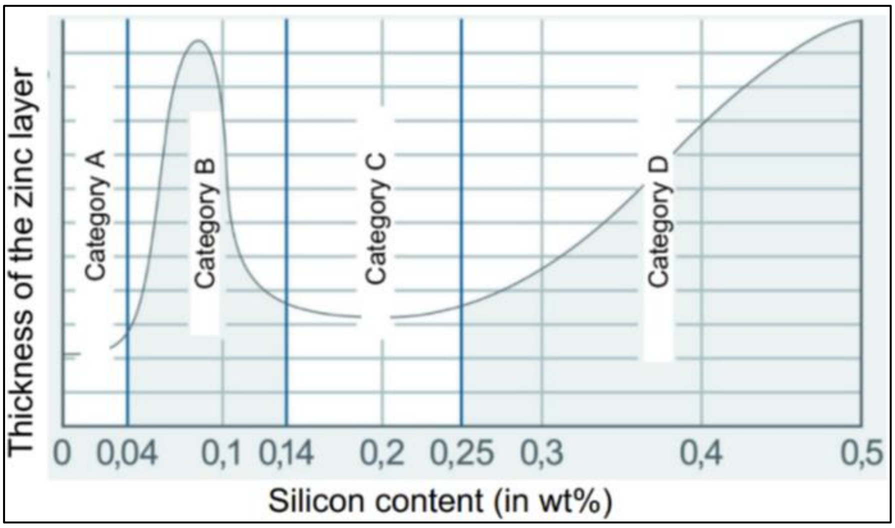

Figure 2: Thickness of the zinc layer depending on the Silicon content of the steel (Institut Feuerverzinken 2015)

& D according to EN ISO 14173-2 like in Figure 2) with different weathering conditions have to be tested to gain an optimized statement of realistic values of the emissivity of such surfaces.

Only few information can be found in literature. In Elich & Hamerlinck (1990), the emissivity of galvanized steel sheetings for temperatures between 400°C and 450°C is about 0.1 – 0.2. In Figure 3, the influence of oxidation and melting of the zinc layer can be clearly seen, which leads to a significant increase in the emissivity. However at higher temperatures, there is no difference in emissivity between galvanized and other steel surfaces.

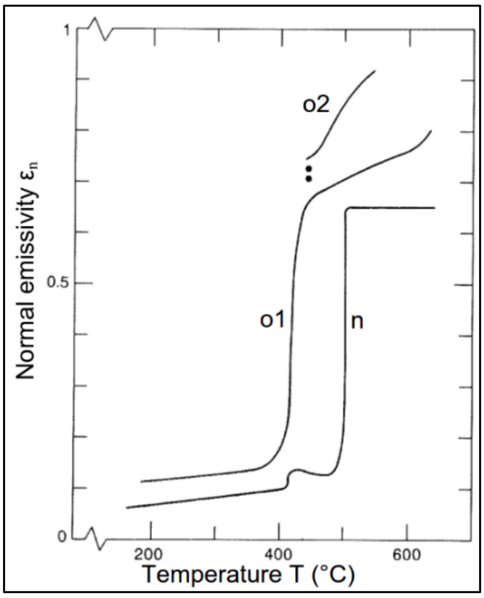

Figure 3:Directed emissivity perpendicular to the surface for sendzimir-galvanized 'old' (o) and 'new' (n) sheets (Elich & Hamerlinck 1990)

The following Table 2 compares the maximal possible degree of utilization for galvanized and ungalvanized members with a concrete slab on top at 30 minutes of fire exposure. The colours illustrate the positive effect that could be possible according to Elich & Hamerlinck depending on the section factor. Green: R30 requirement is ensured; Yellow: additional measures have to be done, such as a lower utilization ratio of the steel member; White: for members with high A_M/V-values, which are typical for secondary beams of composite structures, the influence of the emissivity of the section surface is much smaller and hardly any beneficial effect to the fire resistance can be expected. Nevertheless, due to membrane action of composite slabs in fire, those members can stay unprotected anyway.

Table 2: Comparison of the maximal possible degree of utilization μ_0 for galvanized and ungalvanized members with a concrete plate on top at 30 minutes

Profiles	**$[A_m/V]_b$**	**$[A_m/V]_b$**	**$\theta_{a,Zinc,}$ 30 min**	**$\theta_{a,blank,}$ 30 min**	**$\Delta\theta_a$**	**μ_0 Zinc**	**μ_0 blank**	**$\kappa = 0{,}7$**	**$\kappa = 0{,}7$**
			(var. ε)	**ε nach EC 3-1-2**				**$\mu_{0,\,Zinc}$ / 0,7**	**$\mu_{0,\,blank}$ / 0,7**
HEM 200, HEM 700	45-50	47,5	387	654	267	0,99	0,32	**1,41**	**0,46**
HEB 450, HEB 700, HEM 1000	51-55	52,5	413	678	265	0,97	0,27	**1,38**	**0,39**
HEB 300, HEB 320, HEB 600, HEB 650, HEB 800, HEB 1000	56-60	57,5	476	697	221	0,86	0,24	**1,23**	**0,34**
HEA 500, HEA 600, HEA 700, HEA 900, HEB 280, HEM 120	61-65	62,5	543	712	169	0,64	0,22	**0,91**	**0,31**
HEA 360, HEA 450, HEA 1000	66-70	67,5	597	723	126	0,46	0,20	**0,66**	**0,29**
HEA 320, HEB 220	71-75	72,5	641	730	89	0,35	0,19	**0,50**	**0,28**
HEA 300, HEB 200	76-80	77,5	675	734	59	0,28	0,19	**0,40**	**0,27**
HEA 280, HEB 180	81-85	82,5	701	737	36	0,23	0,18	**0,34**	**0,26**
HEA 260, HEB 160	86-90	87,5	719	740	21	0,21	0,18	**0,30**	**0,26**
IPE 600, HEA 240	91-95	92,5	730	745	15	0,19	0,18	**0,28**	**0,25**
IPE 550, HEA 220, HEB 140	96-100	97,5	735	750	15	0,19	0,17	**0,27**	**0,24**
IPE 450, HEA 200	101-110	105	742	760	18	0,18	0,16	**0,26**	**0,23**
IPE 400, HEA 180, HEB 100	111-120	115	759	772	13	0,16	0,15	0,23	0,21
IPE 360, HEA 140	121-130	125	777	784	7	0,14	0,14	0,20	0,19
IPE 300, IPE 330, HEA 120	131-140	135	792	794	2	0,13	0,13	0,18	0,18
IPE 270 bis IPE 120	141-150	145	804	802	-2	0,12	0,12	0,17	0,17

PRELIMINARY TESTS

TEMPERATURE DEVELOPMENT TESTS

Before starting a deeper research, some pre-tests were performed to measure the temperature development in different samples in a fire test according to the ISO 834 fire curve. The preliminary tests, as well as the upcoming full scale tests, take place in the fire test laboratory of the Technical University of Munich. The first test specimen – in this case small plates with various surfaces, like rusted, galvanized or blank steel and also with different A_M/V-values were fixed at the top of the furnace. During the fire test, the temperature of the plates was measured with thermocouples fixed in the test samples, while the temperature in the furnace was measured with so called plate-thermocouples.

Figure 4: Furnace (left) & test specimen with different surfaces (right)

The diagram (Figure 5) shows on the one hand the standard temperature time curve (dashed, blue) and therefore the gas temperature in the furnace and on the other hand the measured temperatures of different galvanized specimen. The diagram proofs further that the influence of the different A_M/V-values is significant. For example, the difference between a 20 mm thin plate (orange, “Zinc_20”; A_M/V=113 [1/m]) and a 30 mm thick plate (red, “Zinc_30”; A_M/V=80 [1/m]) is about 100°C after 20 minutes. After 40 minutes, the fire test was stopped due to the research’s assumption that only a R30 requirement needs to be reached.

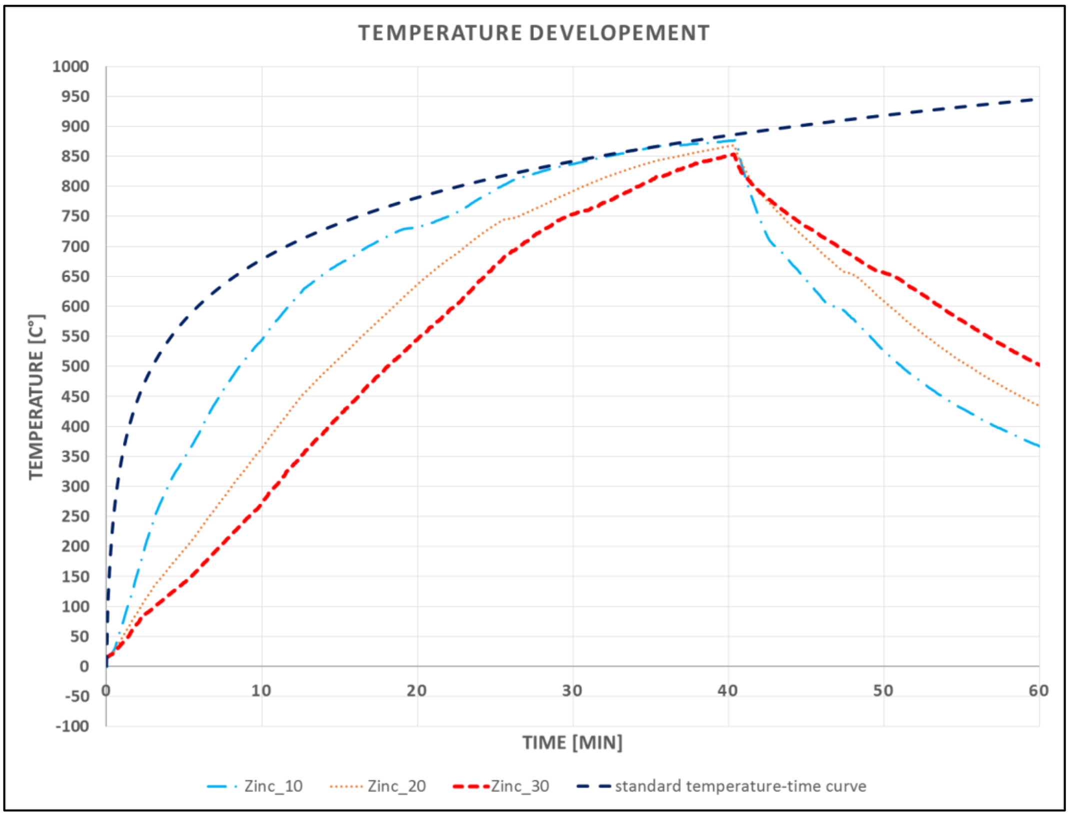

Figure 5: Preliminary Test – Temperature development

The emissivity of the preliminary test samples was obtained by retroactive accounting. For a specimen with an A_M/V-value of about 113 (thickness 20 mm) –a relative high one (white colour in Table 1) – the blue curve (εm,20) in Figure 6 was obtained. The received emissivity varies between 0.38 and 0.77 within the fire development and is thus especially at the beginning of a fire smaller than the constant red line which is the given emissivity from the Eurocode.

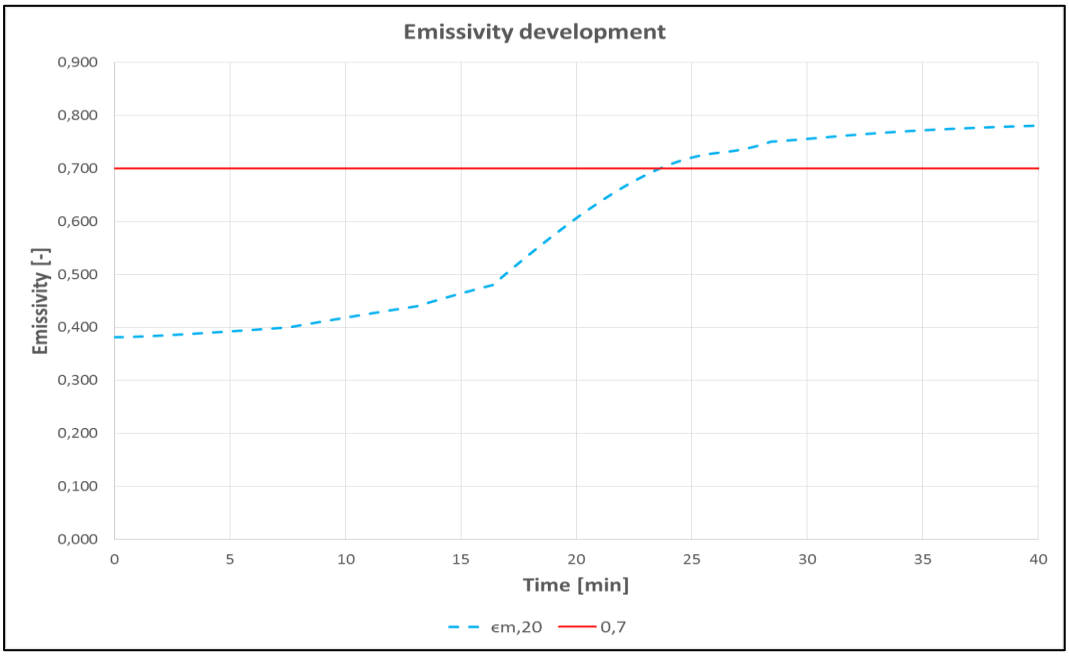

Figure 6: Preliminary Test – Emissivity development

The “recalculated” temperature development (“T,a (ε=var)” in Figure 7) was then compared to the curve obtained by the Eurocode with a constant emissivity ε = 0,7 (“T,a (ε=0,7)” in Figure 7). The difference of the two calculated temperature developments is up to nearly 100 °C at 13 minutes of fire exposure but due to the high A_M/V-value the temperature curves approximate within the ongoing process.

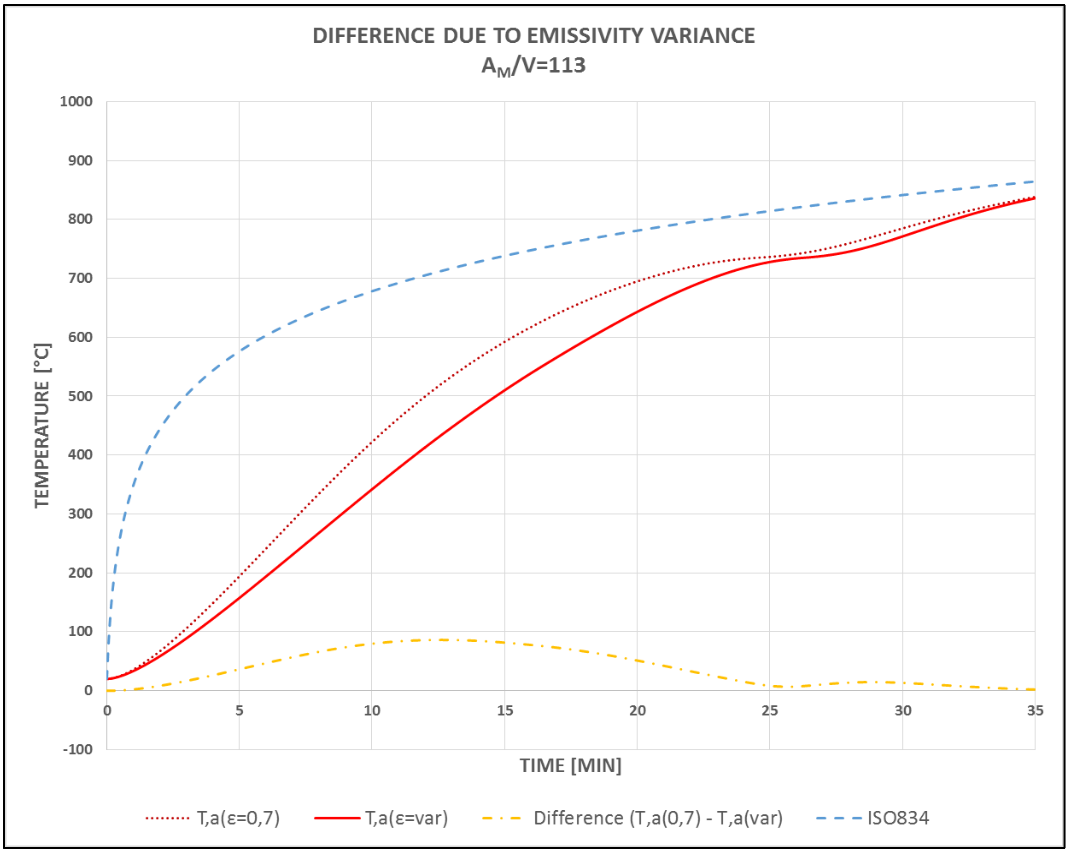

Figure 7: Preliminary Test - Temperature-Time-Curve (A_M/V=113)

FUTURE TESTS - EXPERIMENTS TO DETERMINE THE TEMPERATURE DEPENDING EMISSIVITY

To obtain an adequate data base for the definition of a variable emissivity of hot-dip galvanized members, the temperature dependent hemispheric emissivity has to be determined first by small-scale tests. The measurement of the hemispherical emissivity thus has to take into account the wavelength, the polar angle and the temperature dependency of the emissivity.

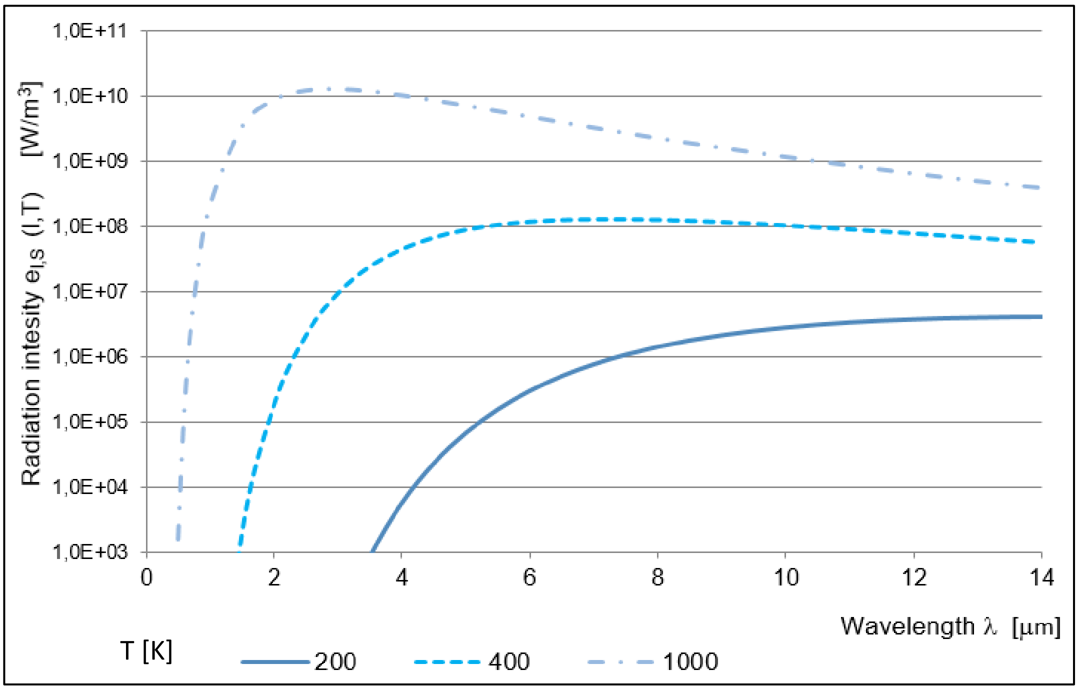

Figure 8: Radiation intensity in dependence of the wavelength and the temperature (Polifke & Kopitz 2009)

Therefore the samples are equipped with thermocouples in order to verify the temperature at the surface. In addition two pyrometers were used to measure the temperature and to determine the emissivity. With an angle respectively directional dependents of the emissivity (Figure 9) a range of at least π/3 (-60°) to π/3 (60°) has to be covered to get a precise measurement of the oriented emissivity. To provide this, the specimens are fixed on a rotatable plate and will be precisely controlled by a stepper motor. Two pyrometers, fixed on a construction in a defined distance, measure at different wavelengths to assure the relevant wavelength range from λ = 1 µm to λ = 5 µm.

In this small scale tests, the heating is provided from the back of the specimen to minimize the disturbance for the measurement of the front surface. Two different furnace variants are thought to be tested. The first variant is a modified muffle furnace and the second one is a self-built solution with a coil surrounded by insulating boards. A temperature development from 20°C to about 850°C is sought. With a change of the section's temperature, a change of emissivity is accompanied. By measuring the temperature with help of infrared sensors and comparing these measurements with the temperature measurements by the thermocouples on the test specimen itself, it is possible to determine the targeted emissivity.

The advantages of these small scale tests are on the one hand that during the determination of the surface's emissivity they allow to exclude effects from convection, to eliminate the influence of the emissivity of the fire compartment itself and on the other hand that they exclude the shadow effect in case of certain section types.

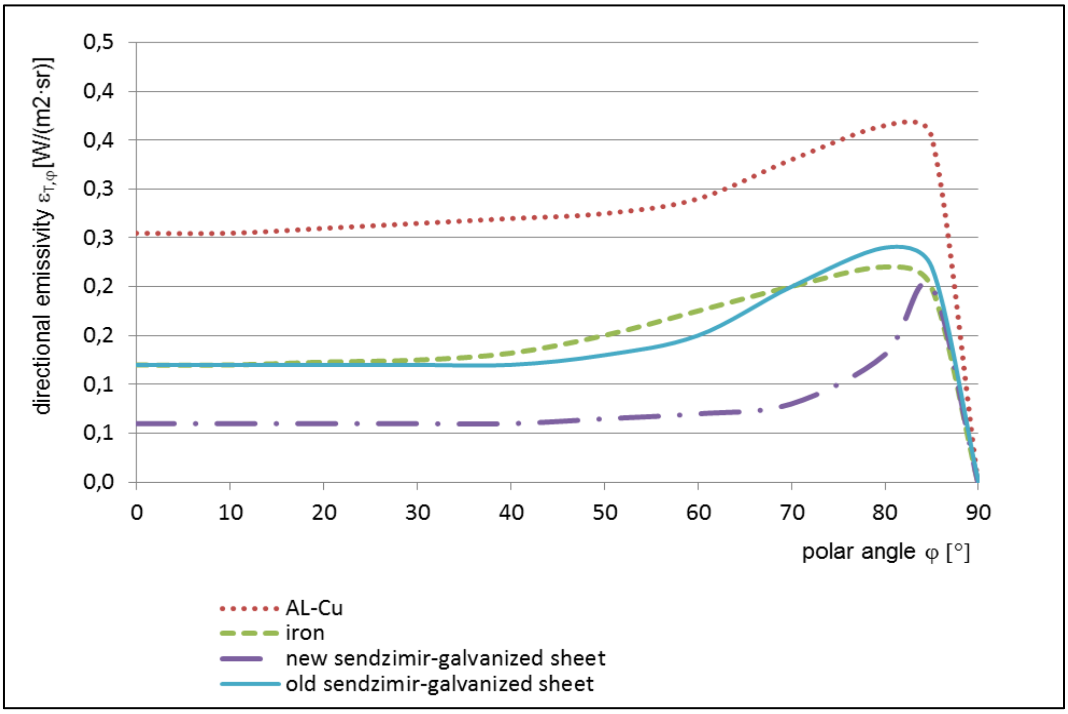

Figure 9: directional emissivity in dependence of the polar angle (Al-Cu and iron according to Polifke & Kopitz 2009; sendimir-galvanized sheet according to Elich & Hamerlinck 1990)

After the small scale tests, the thermal behaviour of galvanized and ungalvanized steel components under ISO fire scenario conditions will be investigated experimentally in three large-scale tests in the fire laboratory in order to include the effects from convection and to verify the findings of the small scale tests under conditions close to real fires. During the fire tests, the temperatures of the walls and the ceiling in addition to the measurement of the temperature in the fire area are measured to take account of the radiation of these in the evaluation of the tests.

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