CFD Modelling of Water Spray Impingement Cooling

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Abstract

In fire dynamics, water spray surface cooling can be particularly efficient in (*i*) preventing the pyrolysis of combustible materials (to limit flame spread and fire growth) and (*ii*) avoiding excessive heating of structural elements, which can potentially lead to structural damage. The development of reliable numerical tools can therefore assist in the design of efficient mitigation measures. For that purpose, it is important to correctly model the convective heat transfer coefficient, h_w, of water droplets impinging onto the surface of a solid material.

It is in this context that numerical simulations of water spray surface cooling have been carried out with the Fire Dynamics Simulator (FDS 6.8.0), a Computational Fluid Dynamics (CFD) code developed by the National Institute of Standards and Technology (NIST, US). This is a continuation of the validation work of Cédric Van de Vondel (UGent)[1], but relying on a new experimental campaign. The experimental configuration examined at the LEMTA laboratory at the University of Lorraine in France consists of a 1 m × 1 m plate, made of 3.1-mm thick steel, positioned horizontally and heated centrally from below by a radiant panel. During the heating phase, the steel surface temperature reached (at the center) steady-state values between 300 and 660°C, depending on the flow rate of the gas feeding the radiant panel. As opposed to a previous experimental campaign, the radiant panel is kept on and a 60° conical jet nozzle positioned at 0.5 m above the steel plate is activated, delivering a flow rate between 5 and 10 L/min, with a volume-median droplet diameter of about 220 to 245 µm.

It is found that the former default value of $h_w = 300$ W/(m^2·K) in FDS generally underestimates the cooling rate. An empirical correlation based on the local Nusselt number for a turbulent flow over a surface generally provides better results. Nevertheless, some challenges remain regarding specific test cases where, in the modelling, excessive water evaporation prior to impingement results in a significant cooling delay.

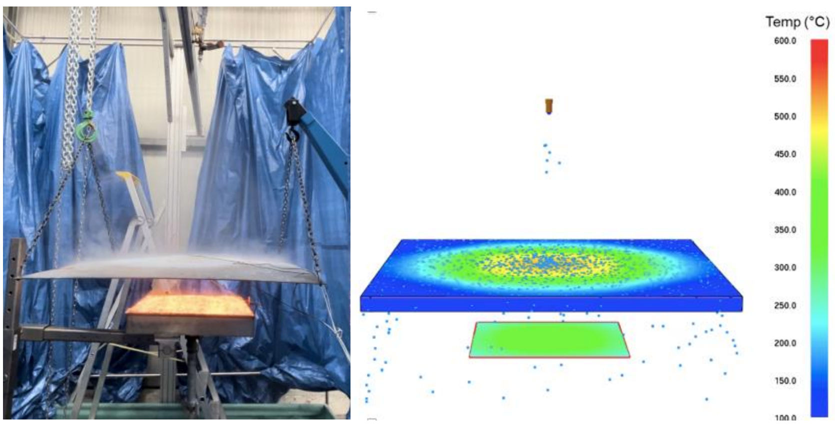

Figure 1 – Photo of the experimental set-up (left) and a snapshot of a CFD simulation (right).

[1] https://imfse.be/theses

1. Introduction

In fire dynamics, water spray surface cooling can be particularly efficient in (*i*) preventing the pyrolysis of combustible materials (to limit flame spread and fire growth) and (*ii*) avoiding excessive heating of structural elements, which can potentially lead to structural damage.
The development of reliable numerical tools can therefore assist in the design of efficient mitigation measures. For that purpose, it is important to correctly model the convective heat transfer coefficient, h_w, of water droplets impinging onto the surface of a solid material.
It is in this context that numerical simulations of water spray surface cooling have been carried out with the Fire Dynamics Simulator (FDS 6.8.0) [1, 2], a Computational Fluid Dynamics (CFD) code developed by the National Institute of Standards and Technology (NIST, US).
The CFD validation study described in this paper is based on an experimental campaign carried out at the LEMTA laboratory at the University of Lorraine in France [3].
The paper briefly describes the experimental configuration and the numerical settings before analyzing the main results and formulating the main conclusions and elements of future work (with respect to the prediction of water spray impingement cooling).

2. Experimental configuration

2.1 Heating of the steel plate

The experimental configuration examined at the LEMTA laboratory at the University of Lorraine in France [3] consists of a 1 m × 1 m plate, made of 3.1-mm thick steel, positioned horizontally and heated centrally 20 cm from below by a radiant panel (0.5 m × 0.5 m). During the heating phase, the steel surface temperature reached (at the center) steady-state values between 300 and 670°C, depending on the flow rate of the gas feeding the radiant panel (from 0.25 to 1.40 g/s).

2.2 Water spray parameters

As opposed to a previous experimental campaign, the radiant panel is kept on and a 60° (half-angle) conical jet nozzle positioned at 0.5 m above the steel plate is activated, delivering a flow rate of 5 and 10 L/min, with a volume-median droplet diameter of about 220 to 245 µm. The water pressure has been maintained at 6 bar. Furthermore, other parameters provided in [3] and the technical datasheet of the Tyco Protectospray D3 nozzle [4] are specified in Table 1.

Table 1 – Nozzle and droplet size distribution parameters.

	TG-SS5	TG-SS10
Pressure (bar)	6	6
Flow rate (L/min)	5	10
Orifice diameter (mm)	2.08	2.77
Spray half-angle (°)	59	62
$D_{v,50}$ (µm)	212	224
γ (-)	3.16	3.16

The surface temperatures were measured using K-type thermocouple wires welded directly to the surface of the plate in a separate contact. This technique provides an accurate measurement of the surface temperature during the cooling [5]. The positioning of the thermocouples (TCs) is provided in Fig. 2 and Table 2 for both the top 'cooled side' (exposed to the water spray) and the bottom 'heated side' exposed to the radiant panel. For the sake of conciseness, the analysis in this paper is focused on TC-1 (in the center of the cooled side) and TC-5 (near the corner of the cooled side).

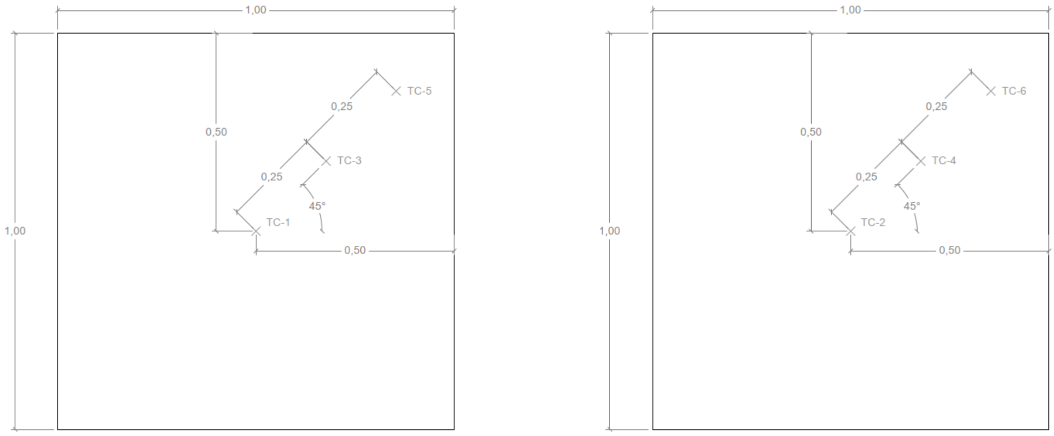

Figure 2 – Sketch of the thermocouple positioning on the cooled (left) and heated (right) sides of the plate [3].

Table 2 – Thermocouple positioning (in Cartesian coordinates) on the cooled (left) and heated (right) sides of the plate [3].

Thermocouple Number	Location	
	x	*y*
Cooled Side		
TC 1	0.00	0.00
TC 3	0.21	0.21
TC 5	0.35	0.35
Heated Side		
TC 2	0.00	0.00
TC 4	0.21	0.21
TC 6	0.35	0.35

3. Numerical modelling

The numerical simulations have been carried out with the Fire Dynamics Simulator (FDS 6.8.0) [1, 2] following a stepwise approach by simulating first solely the heating phase of the steel plate. Then, the water sprays have been simulated in ‘cold conditions’, *i.e.* in the absence of heating. After achieving good simulation results for these two stages (*e.g.* with respect to mesh sensitivity or reaching a good agreement for the steel temperature prior to cooling), simulations of the complete setup have been carried out, including both the heating and the cooling phases. For sake of conciseness, only the latter set of ‘final simulations’ are reported in this paper.
Furthermore, it is important to state that, unless mentioned otherwise, the default parameters of FDS 6.8.0 have been used.
A computational domain of 1.2 m × 1.2 m × 1.2 m has been prescribed along with an ‘`OPEN`’ boundary condition (*i.e.* total pressure boundary condition) for all sides. The initial temperature is prescribed according to the experimental data.
More details on the numerical modelling are provided hereafter.

3.1 Heating of the plate

The heating of the plate is simulated by solving 1D Fourier's equation in the direction normal to the steel plate. The specified steel density is 7800 kg·m^{-3}. The specific heat, c_p, and thermal conductivity of steel, k, are specified as a function of temperature based on experimental measurements reported in [5], see Table 3.

Table 3 – Thermal conductivity and heat capacity of steel [5].

Temperature (°C)	200	300	400	500	600	700
$k\ (W \cdot m^{-1} \cdot K^{-1})$	51.1	44.5	39.1	34.8	31.7	32.2
$c_p (J \cdot kg^{-1} \cdot K^{-1})$	500.3	526.4	554.6	608.9	707.4	851.6

The heating is simulated by specifying the heat flux (in kW·m^{-2}) on a solid surface using the `NET_HEAT_FLUX` function. In these cases, the defined heat flux value must be positive to indicate that the defined surface or obstruction is heating the surroundings. First, an estimate of the heat flux is calculated. Then, an iterative procedure (a few trial and error simulations) is carried out to obtain the best agreement in terms of steel plate temperature. The device `WALL_TEMPERATURE` is used in FDS to monitor the surface temperature.

3.2 Water spray parameters and surface cooling

3.2.1 Water spray parameters

The water pressure and the spray angle (provided in Table 1) have been prescribed in the simulations. Additionally, the K-factor has been prescribed based on the water flow rate and the pressure (provided in Table 1). Finally, the prescribed initial droplet velocity (*i.e.* `PARTICLE_VELOCITY`) has been estimated based on the water flow rate and the orifice diameter (provided in Table 1). Finally, the default 'Rosin-Rammler-Lognormal' distribution has been prescribed for the droplet size distribution.

3.2.2 Surface cooling

Surface cooling is estimated by calculating the corresponding heat flux as:

$$\dot{q}_w'' = h_w \left(T_g - T_p\right) \qquad (1)$$

where h_w is the convective heat transfer coefficient between the water droplets and the steel plate, T_p is the steel plate surface temperature, and T_g is the gas temperature in the first CFD cell adjacent to the surface.

The coefficient h_w can be prescribed as a constant (h_w = 300 W/(m^2·K) by default in former FDS versions) or using the following expression:

$$h_w = \frac{\mathrm{Nu} \times k_g}{L} \qquad (2)$$

where Nu is the Nusselt number, k_g is the thermal conductivity of the fluid or the material in contact with the fluid and L is a characteristic length (see [1, 2] for more details).

The Nusselt number is expressed as:

$$\mathrm{Nu} = 0.0296\,\mathrm{Re}^{4/5}\mathrm{Pr}^{1/3} \qquad (3)$$

where Re is the Reynolds number and Pr is the turbulent Prandtl number (see [1, 2] for more details).

3.3 Numerical parameters

A structured uniform mesh has been applied in all simulations. A mesh sensitivity analysis has been carried out by considering three cell sizes: 10.0 cm, 5.0 cm and 2.5 cm. The results indicate that a good convergence is obtained with a 5.0 cm cell size.
Furthermore, in some simulations, the number of radiation angles has been increased from the default value of 100 to 200 without obtaining a significant change in the results.
Finally, a sensitivity analysis on the number of computational droplets has shown that increasing the default value of 5,000 droplets per second did not yield significantly different results.

4. Results

Figure 3 (left) shows that for a burner flow rate of 0.25 g/s and water flow rate of 5 L/min, the correlation for the convective heat transfer coefficient gives a better agreement with the experimental data, particularly for the thermocouple TC-1 positioned at the center of the plate, where the steady-state temperature prior to water spray activation is about 300°C.
At the edge of the plate (thermocouple TC-5), where the steady-state temperature prior to water spray activation is below 100°C, there are marginal differences between the two modeling options for the convective heat transfer coefficient, see Figure 3 (right). The cooling rate in both cases is quite low (lower than in the experiment) because of the low temperature combined with a position that is remote from the water impingement point.

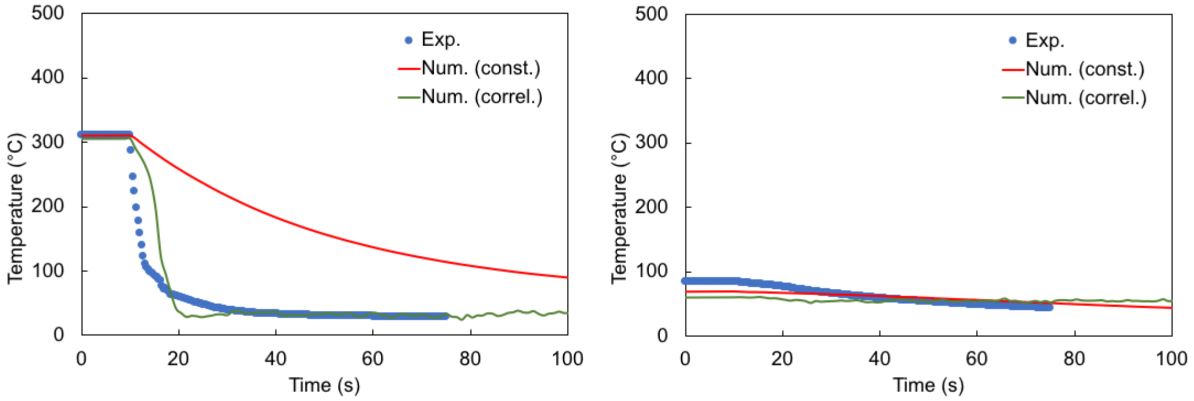

Figure 3 – Comparison between experimental and numerical data (constant h_w vs. correlation) for the steel plate surface temperature TC-1 at the center (left) and TC-2 at the corner (right) of the cooled side for a burner flow rates of 0.25 g/s and a water flow rate of 5 L/min (*i.e.* TG-SS5 nozzle).

Figure 4 (left) shows that increasing the burner flow rate to 1.40 g/s, which corresponds to a temperature at the center of nearly 670°C prior to spray activation, yielded similar trends for the constant convective heat transfer coefficient of 300 W/(m^2·K), that is an underestimated cooling rate (*i.e.* slow decay of the temperature). However, as opposed to the burner flow rate of 0.25 g/s, the results for the correlation were even worse; there is hardly any temperature reduction within the first 100 s at for the thermocouple TC-1. This is explained as follows. The higher burner flow rate leads to a higher temperature at the surface of the steel plate, that is 670°C. As a consequence, convective and radiative heating from the plate are more pronounced, which promotes the heating and evaporation of the droplets travelling from the nozzle to the steel plate. This is believed to significantly reduce the Reynolds number of the droplets, Re_d, because the latter is proportional to the droplet diameter, which is lower due to evaporation. Hence the convective heat transfer coefficient calculated from the correlation becomes too low to trigger a sufficiently pronounced cooling. A minimum cooling rate is ensured by the constant convective heat transfer coefficient approach but, in this case, the value of 300 W/(m^2·K) is too low to provide a good agreement with the experimental data.
Figure 4 (right), with the temperature at the edge (TC-5) reaching a value of about 200°C, a better performance of the correlation is obtained. This is similar to Figure 3 (left).

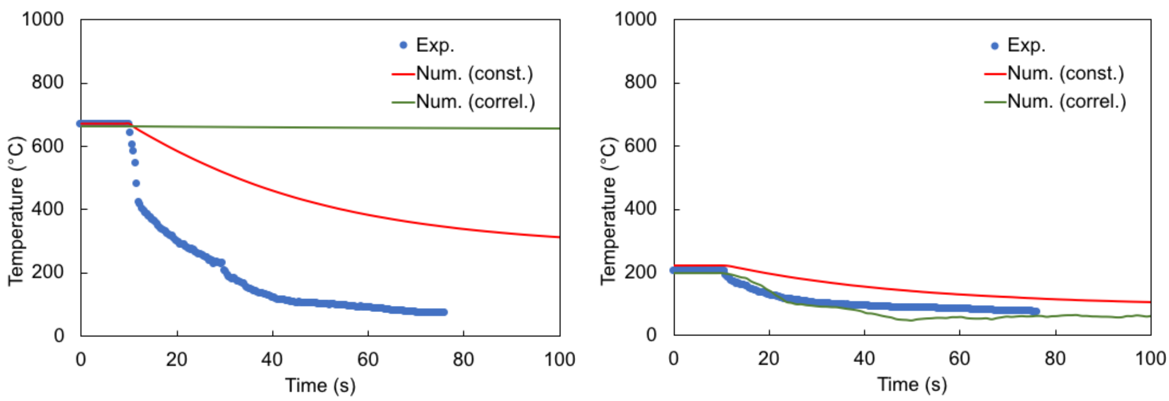

Figure 4 – Comparison between experimental and numerical data (constant h_w vs. correlation) for the steel plate surface temperature TC-1 at the center (left) and TC-2 at the corner (right) of the cooled side for a burner flow rates of 1.40 g/s and a water flow rate of 5 L/min (*i.e.* TG-SS5 nozzle).

Based on the results displayed in Figs. 3 and 4, it appears that when the steel temperature is between about 200 and 300°C, the correlation performs better than the constant value. For temperatures as high as 670°C, the correlation does not yield to any cooling and the constant value significantly underestimates the cooling rate.

The results displayed in Figs. 5 and 6 for a water flow rate of 10 L/min generally confirm the conclusions drawn from Figs. 3 and 4, except for Fig. 6 (left). It appears that thanks the higher water flow rate of 10 L/min in this case (as opposed to 5 L/min in the previous case) a high cooling rate, close to the experimental value, is predicted with the correlation except that the cooling phase is initiated with a delay between approximately 20 and 200 s. Other results (not shown here) confirm that the higher the steel temperature (depending on the gas flow rate and the thermocouple position), the longer the time delay. Further work is needed to understand this behavior.

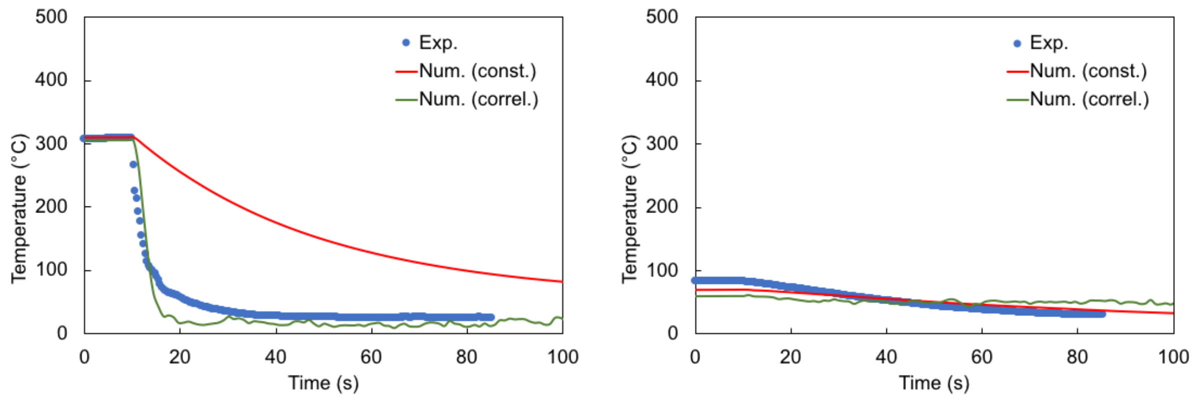

Figure 5 – Comparison between experimental and numerical data (constant h_w vs. correlation) for the steel plate surface temperature TC-1 at the center (left) and TC-2 at the corner (right) of the cooled side for a burner flow rates of 0.25 g/s and a water flow rate of 10 L/min (*i.e.* TG-SS10 nozzle).

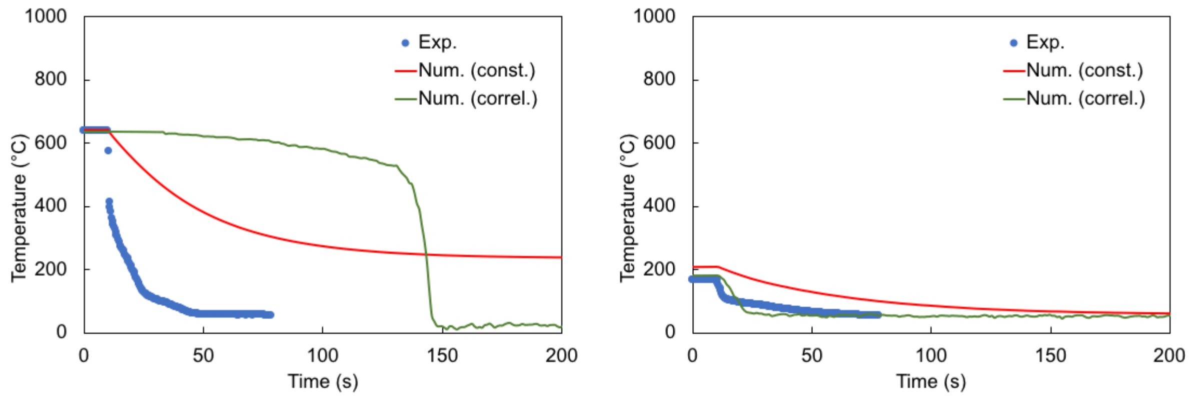

Figure 6 – Comparison between experimental and numerical data (constant h_w vs. correlation) for the steel plate surface temperature TC-1 at the center (left) and TC-2 at the corner (right) of the cooled side for a burner flow rates of 1.00 g/s and a water flow rate of 10 L/min (*i.e.* TG-SS10 nozzle).

5. Conclusions

The paper presents a CFD validation study using the Fire Dynamics Simulator (FDS 6.8.0) for the configuration of a water spray impingement cooling onto a horizontal steel plate. Several steel temperatures and water flow rates have been considered. The analysis is focused on the modelling of the convective heat transfer coefficient, h_w, of water droplets impinging onto the surface. It appears that the former default value of h_w = 300 W/(m^2·K) in FDS generally underestimates the cooling rate. An empirical correlation based on the local Nusselt number for a turbulent flow over a surface generally provides better results. Nevertheless, some challenges remain regarding specific test cases where, in the modelling, excessive water evaporation prior to impingement results in a significant cooling delay. In fact, based on the collaborative work between the National Institute of Standards and Technology (NIST, US), the LEMTA laboratory (France) and Ghent University (Belgium), the latest FDS version relies on the following expression:

$$h_w = \max\left(100, \frac{\mathrm{Nu} \times k_g}{L}\right); \; \mathrm{Nu} = 0.0296\,\mathrm{Re}^{4/5}\mathrm{Pr}^{1/3} \qquad (4)$$

where the value of 100 W/(m^2·K) is a minimum value of the convective heat flux, which ensures a minimum level of cooling in case of strong underestimation of the empirical correlation (as shown in this paper). More correlations will be examined in the future and more validation studies will be carried out.

References

[1] K. B. McGrattan, R. McDermott, M. Vanella, E. Mueller, S. Hostikka, and J. Floyd, “Fire Dynamics Simulator User’s Guide (Sixth Edition),” Gaithersburg, MD, Apr. 2023. doi: 10.6028/NIST.SP.1019.

[2] K. B. McGrattan, S. Hostikka, J. Floyd, R. McDermott, M. Vanella, and E. Mueller, “Fire Dynamics Simulator Technical Reference Guide (Sixth Edition),” Gaithersburg, MD, Apr. 2023. doi: 10.6028/NIST.SP.1018.

[3] L. Cappon, “Study of the cooling of a metal plate at high temperature by water spraying,” Master thesis dissertation, Université de Lorraine, Nancy, 2024.

[4] Tyco, “Type D3 Protectospray Directional Spray Nozzles, Open, Medium Velocity,” Aug. 2023 Accessed: Jan. 10, 2024. [Online]. Available at: docs.jci.com/tycofire/tfp802

[5] Z Acem, V Dréan, G Parent, A Collin, A Wilhelm, T Beji, R Mehaddi, Water Sprays Cooling of a Hot Metallic Plate, Fire Technology, 1-17, https://doi.org/10.1007/s10694-024-01617-6.

Appendix: An example of an FDS input file from the Master thesis of Pedro Vargas (IMFSE)

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&HEAD CHID='H_TG5', TITLE='H_TG5'/

&MESH IJK= 48, 48, 12, XB= -0.60, 0.60, -0.60, 0.60, -0.45, -0.15, MPI_PROCESS=0 /

&MESH IJK= 48, 48, 12, XB= -0.60, 0.60, -0.60, 0.60, -0.15, 0.15, MPI_PROCESS=1 /
&MESH IJK= 48, 48, 12, XB= -0.60, 0.60, -0.60, 0.60, 0.15, 0.45, MPI_PROCESS=2 /
&MESH IJK= 48, 48, 12, XB= -0.60, 0.60, -0.60, 0.60, 0.45, 0.75, MPI_PROCESS=3 /
&MESH IJK= 48, 48, 12, XB= -0.60, 0.60, -0.60, 0.60, 0.75, 1.05, MPI_PROCESS=4 /
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&TIME T_END= 1050/
&MISC TMPA= 12.0 /

&DUMP DT_RESTART = 50.0 /
/&MISC RESTART =.TRUE. /

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&SPEC ID= 'METHANE' /

&MATL ID                                = 'STEEL'
      DENSITY                           = 7800.0
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      SPECIFIC_HEAT_RAMP         = 'c_ramp' /

&RAMP ID= 'k_ramp', T= 200., F= 51.1 /
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&RAMP ID= 'k_ramp', T= 700., F= 32.2 /

&RAMP ID= 'c_ramp', T= 200., F= 0.5003 /
&RAMP ID= 'c_ramp', T= 300., F= 0.5264 /
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&RAMP ID= 'c_ramp', T= 500., F= 0.6089 /
&RAMP ID= 'c_ramp', T= 600., F= 0.7074 /
&RAMP ID= 'c_ramp', T= 700., F= 0.8516 /

&SURF ID                               = 'STEEL PLATE'
      MATL_ID                          = 'STEEL'
      THICKNESS                        = 0.0031 /



/================== RADIATIVE PANEL ==================

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'RED'/ RADIATIVE PANEL: 50x50cm

&RADI NUMBER_RADIATION_ANGLES= 200/

&SURF ID= 'RADIATIVE PANEL'
      NET_HEAT_FLUX             = 28
      RAMP_Q                    = 'NHF_RAMP'
      BACKING                          = 'INSULATED' /

&RAMP ID= 'NHF_RAMP', T=     0.0, F= 0.0 /
&RAMP ID= 'NHF_RAMP', T=     9.9, F= 0.0 /
&RAMP ID= 'NHF_RAMP', T=    10.0, F= 1.0 /

&VENT MB='XMIN', SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /
&VENT MB='YMIN', SURF_ID='OPEN' /
&VENT MB='YMAX', SURF_ID='OPEN' /
&VENT MB='ZMIN', SURF_ID='OPEN' /
&VENT MB='ZMAX', SURF_ID='OPEN' /

/================ WATER SPRAY NOZZLES / SPRAY SET-UP ================

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&PART ID= 'WATER_MIST', SPEC_ID= 'WATER VAPOR', QUANTITIES= 'PARTICLE HEAT TRANSFER
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&PROP ID                               = 'TG-SS5',
      PART_ID                          = 'WATER_MIST',
      OFFSET                    = 0.05,
      SPRAY_ANGLE               = 0., 59.,
      FLOW_RAMP                 = 'SPR_RAMP',
      K_FACTOR                         = 2.04,
      OPERATING_PRESSURE        = 6.00,
      PARTICLE_VELOCITY                = 38.90,
      PARTICLES_PER_SECOND      = 10000 /

&RAMP ID= 'SPR_RAMP', T=    0.0, F= 0.0 /
&RAMP ID= 'SPR_RAMP', T= 800.0, F= 0.0 /
&RAMP ID= 'SPR_RAMP', T= 800.1, F= 1.0 /

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&SLCF PBX= 0.00, QUANTITY='U-VELOCITY’, VECTOR=.TRUE. /
&SLCF PBX= 0.00, QUANTITY='W-VELOCITY’, VECTOR=.TRUE. /

/================== BOUNDARY FILES ==================
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&BNDF QUANTITY='TOTAL HEAT FLUX' /

/================== TC DISTRIBUTION ==================

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&DEVC ID= 'TC_3', XYZ= 0.21, 0.21, 0.00, QUANTITY= 'WALL TEMPERATURE', IOR= 3 /
&DEVC ID= 'TC_5', XYZ= 0.35, 0.35, 0.00, QUANTITY= 'WALL TEMPERATURE', IOR= 3 /


&DEVC ID= 'TC_2', XYZ= 0.00, 0.00, -0.025, QUANTITY= 'WALL TEMPERATURE', IOR= -3 /
&DEVC ID= 'TC_4', XYZ= 0.21, 0.21, -0.025, QUANTITY= 'WALL TEMPERATURE', IOR= -3 /
&DEVC ID= 'TC_6', XYZ= 0.35, 0.35, -0.025, QUANTITY= 'WALL TEMPERATURE', IOR= -3 /

&TAIL /
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