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Numerical Validation of the Two-Way Fluid-Structure Interaction Method for Non-Linear Structural Analysis under Fire Conditions

Donghan Woo¹ and Jung Kwan Seo^{1,2,*}¹ The Korea Ship and Offshore Research Institute, Pusan National University, Busan 46241, Korea; woodh@mmu.ac.kr² Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan 46241, Korea

* Correspondence: seojk@pusan.ac.kr; Tel.: +82-51-510-2415

Abstract: Fire accidents on ships and offshore structures lead to complex non-linear material and geometric behavior, which can cause structural collapse. This not only results in significant casualties, but also environmental catastrophes such as oil spills. Thus, for the fire safety design of structures, precise prediction of the structural response to fire using numerical and/or experimental methods is essential. This study aimed to validate the two-way fluid-structure interaction (FSI) method for predicting the non-linear structural response of H-beams to a propane burner fire by comparison with experimental results. To determine the interaction between a fire simulation and structural analysis, the Fire-Thermomechanical Interface model was introduced. The Fire Dynamics Simulator and ANSYS Parametric Design Language were used for computational fluid dynamics and the finite element method, respectively. This study validated the two-way FSI method for precisely predicting the non-linear structural response of H-beams to a propane burner fire and proposed the proper time increment for two-way FSI analysis.

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Keywords: non-linear structural response; time-variant geometry; Fire Dynamics Simulator; two-way fluid-structure interaction analysis; Fire-Thermomechanical Interface; validation study

1. Introduction

Ships and offshore structures carrying oil and gas are exposed to demanding oceanic and industrial environments with significant fire and explosion hazards. Their structural collapse during fires causes not only significant casualties, but also environmental catastrophes such as oil spills [1]. Many fire accidents on ships and offshore structures have been reported, such as the Sanchi oil tanker accident on 6 January 2018 in the East China Sea and the Piper Alpha accident on 6 July 1998 in the North Sea and the U.S.S. Bonhomme Richard accident on 12 July 2020 in San Diego shown in Figure 1 [2,3].

To prevent the collapse of such large steel structures during fire accidents, structural components must meet the fire resistance ratings of prescriptive codes. These codes were determined based on standard fire-resistance tests, which involved limited structural components and were subjected to a specified time-temperature curve [4]. Fire safety design based on these prescriptive codes is difficult to cover with the actual fire conditions and their structural behavior that a structure is exposed to because they are determined as standard fire load profiles [5,6]. Thus, conventional approaches need to be supplemented by integrated fire safety design approaches based on performance [7,8], which should combine computational fluid dynamics (CFD) and the finite element method (FEM) [8–10].

Figure 1. Sanchi oil tanker (left), Piper Alpha (middle) and U.S.S. Bonhomme Richard (right) accidents.

CFD techniques are a common strategy in fire safety engineering to calculate the multiphysical interactions that occur during a fire [11]. CFD enables fire modeling by solving the basic conservation equations of mass, energy and momentum and using accurate three-dimensional (3D) topological models of structures [7]. CFD code-based software, which is typically represented by FLUENT, CFX, KFX and Fire Dynamics Simulator (FDS), is capable of modeling fire action and has been chosen by researchers to model many fire conditions [12]. CFD modeling has successfully solved various fire safety problems [13]. Paik et al. [7] developed a modeling technique for CFD simulations of fire actions as part of fire engineering of floating production storage and offloading systems.

The FDS developed by the National Institute of Standards and Technology has been widely introduced in fire engineering divisions for modeling various fire scenarios [14]. Many studies have validated the FDS [11,15–19]. The FDS can accurately calculate the values of gas-phase environments, such as temperature, heat flux, velocity and species concentrations, in a variety of fire simulations by comparison with experimental databases [20,21]. The FDS was applied to simulate a medium-scale methanol pool fire and demonstrated reliable predictions of most important parameters of the fire scene compared with experimental results [22]. The FDS was also suggested for modeling jet fire scenarios in process modules to analyze the load characteristics based on experimental data [12].

Many studies have been conducted on the interactions between fire simulations using CFD and structural analysis with the FEM to determine the non-linear structural response to fire. Prasad and Baum [23] proposed formulae to generate realistic thermal boundary conditions using the FDS for coupled transient 3D finite codes. The FDS was used to predict the thermal behaviors of steel columns exposed to localized fires and was validated by comparison with experimental results [24]. Chen et al. [25] developed the Abaqus Fire Interface Simulator Toolkit by integrating the FDS with a customized Abaqus structural analyzer via two-way coupling. Alos-Moya et al. [26] analyzed the non-linear structural response of a bridge to fire based on CFD to create a fire model and finite element software to determine the thermomechanical response. Application of the Eurocode standard and hydrocarbon fires along the full length of the bridge did not adequately represent the fire response of a real bridge. Silva et al. [4,27] validated the Fire-Thermomechanical Interface (FTMI) model to transfer data from the FDS to ANSYS, and compared the experimental results of both the thermal and structural responses of a steel column in a localized fire test. Kim et al. [28] investigated the effect of time increments on the two-way fluid-structure interaction (FSI) analysis of structures subjected to jet fire and suggested an adequate time increment (Δt).

To improve the numerical approach of a two-way FSI for non-linear structural analysis in a propane burner fire, several simulations were conducted and compared with the experimental results of an H-beam. The aims of this study were to (i) perform FSI analysis of an H-beam under a propane burner fire through one-way and two-way analyses, and to then compare the results with experimental data [29], (ii) compare the results of these analyses, depending on the Δt in two-way analysis and (iii) propose an appropriate Δt for two-way FSI analysis.

2. Numerical Approach

2.1. Heat Transfer from Fires

Fire heat energy is transferred from flames and hot gases to the exposed surfaces of a structure by radiation and convection. The total heat flux (q''_{tot}) is the sum of the radiative heat flux (q''_{rad}) and convective heat flux (q''_{conv}), as shown in Equation (1) [30].

$$q''_{tot} = q''_{rad} + q''_{conv} \quad (1)$$

Kirchhoff's law of thermal radiation defines the equality between emissivity (ε) and absorptivity; thus, they can be combined and q''_{rad} can be expressed as Equation (2) [30].

$$q''_{rad} = \varepsilon [e''_{r,abs} - \sigma(T_s)^4] \quad (2)$$

where $e''_{r,abs}$ is the radiative energy absorbed by the exposed surfaces, σ is the Stefan–Boltzmann constant and T_s is the temperature of the exposed surface in Kelvin. Based on Newton's law of cooling, q''_{conv} is defined as the difference between the gas temperature (T_g) adjacent to the exposed surface and T_s multiplied by the convective heat transfer coefficient (h), as shown in Equation (3) [30]. Based on the defined q''_{rad} and q''_{conv} , q''_{tot} can be calculated by Equation (4) [30].

$$q''_{conv} = h(T_g - T_s) \quad (3)$$

$$q''_{tot} = \varepsilon [e''_{r,abs} - \sigma(T_s)^4] + h(T_g - T_s) \quad (4)$$

2.2. Adiabatic Surface Temperature

The FDS provides results that characterize the 3D evolution of a fire, including the q''_{rad} on the exposed surfaces and T_g . However, these results are not capable of accurately reflecting the temperature distribution on exposed surfaces; thus, q''_{tot} cannot be precisely calculated in fire simulations [27]. Adiabatic surface temperature (T_{AST}) was introduced to improve these results [31]. This method replaces the real surfaces to the perfectly insulated surfaces. The q''_{tot} of the ideal surface is defined as zero in Equation (5) [31].

$$\varepsilon [e''_{r,abs} - \sigma(T_{AST})^4] + h(T_g - T_{AST}) = 0 \quad (5)$$

Based on the equal ε and h between the adiabatic surface and the real surface, q''_{tot} is derived by Equation (6). The FDS provides the T_{AST} calculated by Equation (6) and reduces the complexity of the fire simulation into simple scalar data [32–35].

$$q''_{tot} = \varepsilon \sigma [(T_{AST})^4 - (T_s)^4] + h(T_{AST} - T_s) \quad (6)$$

According to the normative procedures of Eurocode 3 [30], h is generally considered to be a constant. However, it varies depending on the fire scenario and relative to q''_{rad} [27]. Thus, the two variables (T_{AST} and h) were measured in the fire simulations and Equation (6) was used to precisely reflect the heat flux.

2.3. FTMI Method

The FTMI was developed by Zhang et al. [4] to create an appropriate boundary condition between the fire simulation of the FDS and the thermomechanical analysis of ANSYS Parametric Design Language (APDL). To correctly map the calculated heat flux from the CFD to FEM models, these models must share the same exposed surfaces. Figure 2 shows a collection of I-keypoints (of x coordinates) positioned at the center of each exposed surface (with normal n) to realize the coupling procedure. The position and the number of I-keypoints are based on the mesh of the FEM model. The coupling procedure can

be achieved for different discretization levels. Thus, the FTMI does not require identical meshes between the CFD and FEM models.

Figure 2. Extent of the concept of the mapping procedure between the finite element method (FEM) and a computational fluid dynamics (CFD) method. FDS: Fire Dynamics Simulator; T_{AST} : adiabatic surface temperature; h : convective heat transfer coefficient; APDL: ANSYS Parametric Design Language.

2.4. Numerical Approach for Two-Way FSI

One-way FSI analysis is generally used for non-linear structural analysis because it is a time-consuming task. However, to precisely reflect the actual structural response to fire load, two-way FSI is necessary. The two-way analysis is affected by the Δt , for which the geometry and fire loads are updated [28]. Figure 3 illustrates the difference between the one-way and two-way FSI for analyzing the non-linear structural response to fire load. The two-way FSI Δt is repeated with updated geometry and material property until the total simulation time.

Figure 3. Differences between the schemes of the one-way and two-way fluid-structure interaction methods for determining the non-linear structural response to fire. Δt : time increment.

Figure 4 shows the analytical logic of a two-way FSI for the non-linear structural analysis of fire in this study. This scheme included the following steps:

- CFD simulation by Δt using the FDS
- Heat transfer analysis and non-linear FEM according to the CFD simulation results
- CFD simulation until the second Δt , and updating the geometry with the previous non-linear FEM
- Repetition of the CFD simulation with the updated geometry and FEM until completion of the fire scenario

Figure 4. Analytical logic of the two-way fluid-structure interaction for determining the non-linear structural response to fire. FDS: Fire Dynamics Simulator; FTMI: Fire-Thermochemical Interface; APDL: ANSYS Parametric Design Language.

This analytical logic can determine the proper Δt for two-way FSI to analyze the non-linear structural response to fire. Generally, the accuracy of the two-way FSI method increases as the Δt decreases. In this study, five different Δt values (4000, 2000, 1000, 500 and 250 s) were introduced to determine the appropriate Δt . If the Δt was the same as the total simulation time (4000 s), this indicated one-way FSI analysis.

- Case I: 4000 s
- Case II: 2000 s
- Case III: 1000 s
- Case IV: 500 s
- Case V: 250 s

Based on the concept of the two-way FSI method, this study introduced the analytical logic with Δt , as shown in Figure 4, and used the FTMI to interact the results of fire simulations of the FDS with the thermal analyses of APDL.

3. Validation Study

A fire experiment on an H-beam commonly used for structural reinforcement in ships and offshore platforms was conducted to obtain data for verification of the thermal-structural analysis technology [29]. The H-beam was 4.20 m in length with a cross-section of 0.10 m (flange) $\times$ 0.15 m (web), a 4.90-mm-thick flange and a 4.30-mm-thick web. ASTM A572-50 steel ($E_{20} = 210$ GPa; $f_{y20} = 413$ MPa) was used to form the H-beam. The boundary condition of the structure was fixed at both ends without a mechanical load. A sand-diffused propane burner (1.00 m $\times$ 0.60 m $\times$ 0.44 m) was used as the fuel and the target heat-release rate (HRR) of 1.8 MW verified with a Coriolis mass flow meters was maintained in the experiment. The fire was extinguished after 60 min. The T_g , steel surface temperature and vertical displacement during combustion were measured. Figure 5 shows the experimental setup [29].

Figure 5. Experimental setup of the H-beam in the propane burner fire.

3.1. Material Properties

The thermal properties of the structural steel in this study were defined according to the Eurocode [30]. The typical ϵ of steel in fire is 0.9. Figures 6 and 7 show the specific heat and thermal conductivity depending on temperature, respectively. To define the stress-strain curve of steel, the representative equations developed by Luecke [36] (Equations (7)–(8)) with $k_1 = 7.820$, $k_2 = 540$ °C, $k_3 = 1006$ MPa, $k_4 = 0.759$ and $n = 0.503$ are introduced. The elastic modulus and yield strength under elevated temperature are defined by Equations (9)–(10) [36].

$$\sigma = \epsilon E_T \quad \left(\epsilon \leq \frac{f_{yT}}{E_T} \right) \quad (7)$$

$$\sigma = f_{yT} + (k_3 - k_4 f_{y20}) \exp \left[- \left(\frac{T}{k_2} \right)^{k_1} \right] \left(\epsilon - \frac{f_{yT}}{E_T} \right)^n \quad \left(\epsilon \geq \frac{f_{yT}}{E_T} \right) \quad (8)$$

$$\frac{E_T}{E_{20}} = \exp \left[- \frac{1}{2} \left(\frac{T - 20}{639} \right)^{3.768} - \frac{1}{2} \left(\frac{T - 20}{1650} \right) \right] \quad (9)$$

$$\frac{f_{yT}}{f_{y20}} = 0.09 + 0.91 \exp \left[-\frac{1}{2} \left(\frac{T-20}{588} \right)^{7.514} - \frac{1}{2} \left(\frac{T-20}{676} \right) \right] \quad (10)$$

$$\alpha_s = 1.17 \times 10^{-5} + 1.34 \times 10^{-8} T - 9.7 \times 10^{-12} T^2 + 1.67 \times 10^{-16} T^3 \quad (11)$$

where E_{20} and E_T are the elastic modulus of steel at room temperature and elevated temperature, respectively and f_{y20} and f_{yT} are the yield strengths of steel at room temperature and elevated temperature, respectively. Figure 8 shows the stress-strain curves calculated by Equations (7)–(10) using the ambient temperature elastic modulus and yield strength of ASTM A572-50 steel ($E_{20} = 210$ GPa; $f_{y20} = 413$ MPa). Equation (11), which was derived by Luecke [36], was used to determine the thermal expansion coefficient (α_s) of steel as the temperature increased. Figure 9 shows the α_s of ASTM A572-50 steel as the temperature increased.

Figure 6. Specific heat of carbon steel as a function of temperature.

Figure 7. Thermal conductivity of carbon steel as a function of temperature.

Figure 8. Stress-strain curve for ASTM A572-50 steel.

Figure 9. Thermal expansion coefficient of ASTM A572-50 steel.

3.2. FDS Simulation of Propane Burner Fire

3.2.1. FDS Model Geometry and Computational Mesh

To obtain an accurate numerical CFD result, an appropriate grid-size composition is crucial [14]. McGrattan et al [14] proposed Equation (12) to determine the necessary spatial resolution for an appropriate large-eddy simulation for a free burning fire in terms of the characteristic diameter of a plume (D^*) [14].

$$D^* = \left(\frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} \sqrt{g}} \right)^{2/5} \quad (12)$$

where $\dot{Q}$ is the HRR, ρ_{∞} is the ambient density, c_p is the specific heat of air at constant pressure, T_{∞} is the ambient temperature and g is the acceleration of gravity. The spatial resolution (R^*) of a numerical grid was derived from Equation (13), where dx is the length of a grid cell [14].

$$R^* = \frac{dx}{D^*} \quad (13)$$

Figure 10 shows the FDS model geometry and the grid composition of all of the planes. The FDS model had a uniform grid size of 0.05 m in all directions, based on $R^* = 1/12$.

Figure 10. Extent of the Fire Dynamics Simulator model geometry (**left**) and the grid composition (**right**).

3.2.2. FDS Results and Discussion

The movement of a flame greatly affects the temperature distribution. However, owing to the asymmetric installation of insulated walls around the experimental setup, the flame movement in the experiment was irregular under an uncontrolled wind flow [29]. Figure 11 shows the difference in the movement of the flame at 60, 180, 720 and 960 s between the experiment [29] and the FDS.

Figure 11. Experimental and computational fluid dynamics scenes of flame movement. FDS: Fire Dynamics Simulator.

The gas cloud temperature was measured at three points, namely GT-1, GT-2, and GT-3, as shown in Figure 12. Figures 13–15 show the gas cloud temperature of the experiments and the FDS. Compared with the experimental results, there were clear differences at all three points in the initial period (approximately 0–500 s). The difference would be caused

by various factors in the experiment. This is presumed to be owing to the unexpected movement of the flame, the irregularly condensed fuel, and the ignition delay in the uncontrolled experimental conditions. However, after the initial period, the gas cloud temperatures in the experiment and FDS showed good agreement at the three points.

Figure 12. Monitoring point locations for the gas cloud temperature and steel temperature.

Figure 13. Gas cloud temperature over time at GT-1.

Figure 14. Gas cloud temperature over time at GT-2.

Figure 15. Gas cloud temperature over time at GT-3.

3.3. Thermal Analysis

To apply the fire load to the structural analysis, T_g must be converted to steel temperature. There are two methods that are used for this process, namely thermal analysis and a heat transfer equation (EN 1993-1-2). Thermal analysis applies the heat flux to the exposed structure using the FTMI. The heat transfer equation calculates the steel temperature using Equation (14) [30]. This equation uses limited monitoring points to measure the time-variant T_g data by the net heat flux, with consideration of convection and radiation. This equation assumes that there is an equivalent uniform temperature distribution throughout the cross-section [30].

$$\Delta\theta_{m,t} = k_{sh} \frac{A_m/V}{c_a \rho_a} h_{net} \Delta t \quad (14)$$

where θ_m is the surface temperature of the steel member, k_{sh} is the correction factor for the shadow effect, A_m/V is the section factor for the unprotected steel member, c_a is the specific heat of steel, ρ_a is the mass density of steel and h_{net} is the net heat flux.

The steel temperatures at the three points in Figure 12 were calculated using two methods and compared with the experimental data of the steel surface, as shown in Figures 16–18. The steel temperatures calculated by the heat transfer equation show a similar rising curve slope at three measuring points with the experimental data during the initial period (0–150 s). However, after the initial period, the steel temperatures using the heat transfer equation at all of the points were higher than the other values. Thus, this would afford a non-linear structural analysis, and thereby lead to an overestimated fire load for the fire safety design of ships and offshore structures.

Figure 16. Steel temperature over time at ST-1.

Figure 17. Steel temperature over time at ST-2.

Figure 18. Steel temperature over time at ST-3.

In Figures 17 and 18, the rising curve slopes of the steel temperatures calculated by the thermal analysis lead to underestimated fire load during the intimal period (0–500 s). However, except for the initial period, the thermal analysis results showed relatively good agreement with the experimental results. Comparing to the results of the steel temperatures calculated by the heat transfer equations, the thermal analysis results reduce the difference with the experimental results. Thus, this numerical method improves the accuracy of the non-linear structural analysis.

4. Results and Discussion

Five cases were considered to determine the appropriate Δt top use in two-way FSI to determine the non-linear structural response of an H-beam to a propane burner fire. The representative values used to determine the effect of the difference in Δt , namely vertical displacements, were measured at three points, namely VD-1, VD-2, and VD-3, as shown in Figure 19.

Figure 19. Measuring points for z-axis displacement over time.

Figures 20–22 show the structural response of the H-beam to a propane burner fire by comparing experimental results with two-way FSI analyses performed using five different

Δt values. The variation shows that two-way FSI analyses should be performed with a fine Δt . Cases IV and V show good agreement in all of the vertical displacement periods. At the final moment (4000 s), Cases IV and V show the difference with the experimental data as 0.09 mm, 0.08 mm at ZD-1, 0.21 mm, 0.19 mm at ZD-2, and 0.56 mm, 0.49 mm at ZD-3 respectively. The numerical predictions lead to errors of less than 21.2%. However, Cases I, II, and III show highly overestimated deformations from approximately 300 s to 1500 s, compared with the experimental data and the final moment (4000 s). Figures 23–25 illustrate the structural responses at 4000 s and the maximum deflection throughout the simulation versus the Δt of two-way FSI to determine the converged Δt . Compared with the experimental results, the Δt of 500 s (Case IV) and 250 s (Case V) are the most suitable for two-way FSI of the H-beam subjected to propane burner fire. The Δt of 500 s (Case IV) is the most efficient for precisely and quickly predicting the structural response of the H-beam to propane burner fire.

Figure 20. Displacement over time at VD-1.

Figure 21. Displacement over time at VD-2.

Figure 22. Displacement over time at VD-3.

Figure 23. Deflection at 4000 s and maximum deflection versus time increments (Δt) at VD-1.

Figure 24. Deflection at 4000 s and maximum deflection versus time increments (Δt) at VD-2.

Figure 25. Deflection at 4000 s and maximum deflection versus time increments (Δt) at VD-3.

Figures 26–28 analyze the reliability of two-FSI for deflection versus time increments (Δt) comparing to experimental data. In Figures 26–28, the mean of Case IV and Case V are 1.0272 and 1.0135 at VD-1; 1.0272 and 1.0209 at VD-2; 1.0337 and 1.0199 at VD-3 respectively. Thus, Cases IV and V have good agreement in all of the vertical displacement periods. Additionally, Case IV and Case V have lower COV than other cases as shown in tables in Figures 26–28.

Figure 29 shows the deformed shapes of the H-beam under a propane burner fire at 4000 s generated by the non-linear structural analysis with different values of Δt .

Figure 26. Statistical analysis results of two-way FSI for deflection versus time increments (Δt) at VD-1.

Figure 27. Statistical analysis of two-way FSI for deflection versus time increments (Δt) at VD-2.

Figure 28. Statistical analysis of two-way FSI for deflection versus time increments (Δt) at VD-3.

Figure 29. Deflection of the H-beam under a propane burner fire at 4000 s.

5. Conclusions

The objectives of this study were to investigate the interactions between fire loads and time-variant geometry under a propane burner fire and the effect of Δt in a two-way FSI analysis. The following conclusions and recommendations for further studies can be drawn.

- One-way FSI tended to overestimate the structural consequences of exposing an H-beam to propane burner fire compared with the experimental results.
- One-way FSI may result in the overestimation of the fire safety design requirements for ships and offshore structures.
- For an H-beam under a propane burner fire, a Δt of 500 s was appropriate for two-way FSI. This use of this Δt also led to a similar structural behavior prediction as that obtained by using a smaller Δt (250 s), both of which were similar to the experimental results.
- As the structural consequences increased over time, the differences between the one-way and two-way FSI methods became more significant. This was a result of the one-way FSI being unable to readjust the fire load characteristics, due to changes in the time-variant geometry.

The appropriate Δt for two-way FSI, with consideration of various fire scenarios and offshore instalments, will be investigated in a future study.

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Nomenclature

Abbreviation

FSI	Fluid-Structure Interaction
FDS	Fire Dynamic Simulator
FEM	Finite Element Method
CFD	Computational Fluid Dynamics
CoV	Coefficient of Variation

Symbols

q''_{tot}	Total heat flux [W/m^2]
q''_{rad}	Radiative heat flux [W/m^2]
q''_{conv}	Convective heat flux [W/m^2]
ε	Emissivity
$e''_{r,abs}$	Radiative energy absorbed by the surfaces [J]
σ	Stefan–Boltzmann constant
T_g	Gas temperature [$^{\circ}C$]
T_s	Multiplied by the convective heat transfer coefficient [$^{\circ}C$]
h	Convective heat transfer coefficient [$W/(m^2 K)$]
T_{AST}	Adiabatic surface temperature [$^{\circ}C$]
Δt	Increment time [s]
E_{20}	Elastic modulus of steel at room temperature [GPa]
E_T	Elastic modulus of steel at elevated temperature [GPa]
f_{y20}	Yield strengths of steel at room temperature [MPa]
f_{yT}	Yield strengths of steel at elevated temperature [MPa]

α_s	Expansion coefficient [1/K]
D^*	Diameter of a plume [m]
$\dot{Q}$	Heat release rate [W]
ρ_∞	Ambient density [kg/m ³]
c_p	Specific heat of air at constant pressure [kJ/kg·K]
dx	Length of a grid cell [m]
R^*	Spatial resolution
θ_m	Surface temperature of the steel member [°C]
k_{sh}	Correction factor for the shadow effect
A_m/V	Section factor for the unprotected steel member [m ⁻¹]
c_a	Specific heat of steel [kJ/kg·K]
ρ_a	Mass density of steel [kg/m ³]
h_{net}	Net heat flux [W/m ²]

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