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Original Article

Electrical fire simulation in control room of an AGN reactor

Jae-Min Jyung [a], Yoon-Suk Chang [b, *]

[a] Graduate School, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Republic of Korea
[b] Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Republic of Korea

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ABSTRACT

Fire protection is one of important issues to ensure safety and reduce risks of nuclear power plants (NPPs). While robust programs to shut down commercial reactors in any fires have been successfully maintained, the concept and associated regulatory requirements are constantly changing or strengthening by lessons learned from operating experiences and information all over the world. As part of this context, it is necessary not only to establish specific fire hazard assessment methods reflecting the characteristics of research reactors and educational reactors but also to make decisions based on advancement encompassing numerical analyses and experiments. The objectives of this study are to address fire simulation in the control room of an educational reactor and to discuss integrity of digital console in charge of main operation as well as analysis results through comparison. Three electrical fire scenarios were postulated and twenty-four thermal analyses were carried out taking into account two turbulence models, two cable materials and two ventilation conditions. Twelve supplementary thermal analyses and six subsequent structural analyses were also conducted for further examination on the temperature and heat flux of cable and von Mises stress of digital console, respectively. As consequences, effects of each parameter were quantified in detail and future applicability was briefly discussed. On the whole, higher profiles were obtained when Deardorff turbulence model was employed or polyvinyl chloride material and larger ventilation condition were considered. All the maximum values considered in this study met the allowable criteria so that safety action seems available by sustained integrity of the cable linked to digital console within operators' reaction time of 300 s.

1. Introduction

Strict management of fires is the prerequisite activity to protect humans and environments by maintaining safety and reducing risks of nuclear power plants (NPPs). In the wake of fire at Browns Ferry in United States, the protection concept and associated regulatory requirements have been changed by accepting lessons learned from operating experiences and information all over the world. For instance, after Fukushima accidents, international standards and national legislations were further strengthened. Hazard analysis should be implemented as one of fourteen factors for periodic safety review (PSR) of NPPs including measures for prevention, detection and suppression of fire according to IAEA safety guide [1]. Relevant provisions were also stated in the safety act and regulation notices of the Nuclear Safety and Security Commission (NSSC) in Korea [2,3].

Recently, a fire hazard assessment of the AGN reactor was conducted according to a regulation notice of NSSC [3], of which draft was first submitted to regulatory agency for review. The assessment for licensing proceeded by judging whether the concrete wall as the final shielding secures sufficient fire resistant-grade when all combustibles in the building are burnt down. In the draft, quantity of the standing combustibles was analyzed in conjunction with floor areas to derive fire loads. Severity of the fire was then evaluated by comparing the duration and resistant-grade sustaining times at the maximum temperature. Whereas this conservative approach is useful in determining fire-induced radiation leaks, it does not deal with the soundness of reactor, internal devices and equipment.

The main causes of NPP fires were reported as electrical, oil and other unknowns. In particular, the rate of electrical fires was the highest as over 60% [4] and the switchgear room was one of high risk areas [5]. Since the most plausible fires may cause reactors to be out of control, the hazard assessment for safety related cables and habitability analyses of operators have been actively conducted

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* Corresponding author.
E-mail address: yschang@khu.ac.kr (Y.-S. Chang).

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[6–9]. While robust protection programs were successfully operated in commercial reactors, non-commercial research and educational reactors have rarely been applied so far. Although IAEA published another safety guide for use of a graded approach for research reactors [10], it is necessary not only to establish specific assessment methods reflecting characteristics of relatively low-powered reactors but also to make decisions based on advanced studies encompassing numerical analyses and experiments [11–13].

If we focus on numerical analyses, concerns will be how to characterize proper scenarios, select appropriate modeling methods and turbulence models, and evaluate structural integrity [14]. The scenarios are defined by combining ingredients needed to simulate fires through identifying locations of ignition sources and targets, heat release rates from ignition sources and ventilation conditions etc. [5]. Modeling methods can also be classified into three types; in short, both simple algebraic correlation and zone or lumped parameter methods are difficult to apply in practical fire situations due to less grids and insufficient input variables. By contrast, computational fluid dynamics (CFD) method allows numerous grids for large space and complex geometries. It predicts fire effects by solving energy conservation and state equations relating to the given elements and surroundings [15].

There are a wide variety of turbulence models for fire simulation as well as thermal hydraulic analyses like large eddy simulation (LES), Reynolds-averaged form of the Navier-Stokes equations (RANS), direct numerical simulation (DNS) and so on. The LES produces more accurate results compared to the RANS when grid sizes are small and provides more economical computation time than the DNS in general. Smagorinsky, Deardorff, wall modeled LES (WMLES) and wall-adapting local eddy-viscosity (WALE) are recognized as usable ones belonging to the LES. Among them, the Smagorinsky model has been widely adopted for fire simulation and the Deardorff model introduced later was proven through some large scale experiments [15]. Hence, it is necessary to compare results of thermal analyses using these two LES models and to expand for structural integrity evaluation of equipment that was not considered in usual.

The present study is to address a series of fire simulation of an educational reactor especially in the control room where operators work and control the reactor as well as cables required for safe operation are installed. Also, integrity of digital console in charge of main operation was discussed, as a part of basic data production needed for rational decision making, based on parametric analysis results. In detail, three electrical fire scenarios were postulated because most of fires in NPPs have been induced by relevant ignition sources and twenty-four thermal analyses were carried out; two turbulence models of Smagorinsky and Deardorff, two cable materials of polyvinyl chloride (PVC) and cross-linked polyethylene (XLPE) [16], and two ventilation conditions of 0.67 m^3/s and 0.33 m^3/s [17] were considered. Moreover, twelve supplementary thermal analyses and six subsequent structural analyses were conducted for examination on the temperature and heat flux of cable and von Mises stress of console, respectively.

2. Numerical analyses

2.1. Fire scenarios

The Aerojet General Nucleonics (AGN) educational reactor with a licensed power of 10 W was taken into account. It uses 19.5% enriched UO_2 as fuel, 11 kg of polyethelene as moderator and high density graphite as reflector [18]. Diameter is 1.98 m and height is 2.80 m as outline dimension of reactor itself, and drained weight is 6190 kg. The reactor has been operating in an independent building and divided into several spaces such as reactor room, control room, access room, lecture room, administration room, auxiliary experimental rooms and corridor. In this study, the control room was selected as an important place from the fire risk standpoint, of which size is 7.6 m by 4.3 m and 3.0 m high.

Three electrical fire scenarios were postulated according to ignition sources such as an electrical cabinet, an analog console or both of them. Fig. 1 illustrates schematic with dimensions of the ignition sources and cable installed in the control room of the AGN reactor. The amount, locations and arrangements of cables were directly measured and a couple of strands were modeled as an enveloping bundle for simplicity. While the analog console as well as a digital console is responsible for safe shutdown of the educational reactor, it was assumed that the intended function is available if integrity of the cable linked to the digital console is maintained in the event of fire accidents. Office supplies and fire protecting flexible conduit were excluded for simple and conservative evaluation.

The heat release rates representing characteristics of the ignition sources were grown up to 464 kW for the electrical cabinet and 702 kW for the analog console by 720 s, respectively, as the time-squared parabolic form based on regulatory guidelines [5,19]. The initial temperature was assigned as room temperature and reaction time of operators to suppress fire was set to 300 s as usual. Table 1 represents analysis cases for thermal integrity evaluation according to turbulence models, ignition sources, cable materials and ventilation conditions. Subsequent six structural integrity evaluation cases were summarized in Table 2.

2.2. Turbulence models

It is important to select a turbulence model as suitable for fire simulation. Due to limited space, in lieu of interpreting all the details of two employed ones, the major difference was briefly compared by using key parameters. Both of thermal conductivity (k_t) and mass diffusivity ($(\rho D)_t$) are defined as Eqs. (1) and (2) [14,15,20]. A common but remarkable parameter of turbulence viscosity (μ_t) is determined distinctively in each model.

$$k_t = \frac{\mu_t c_p}{Pr_t} \tag{1}$$

$$(\rho D)_t = \frac{\mu_t}{Sc_t} \tag{2}$$

In Smagorinsky model, it can be derived as the following equation dependent on field property and turbulence specifics. Here, the $|S|$ is calculated as a function of velocity vector and strain tensor like Eq. (4) [20,21]:

$$\mu_t = \rho (C_s \varDelta)^2 |S| \tag{3}$$

$$|S| = \left(2 S_{ij} S_{ij} - \frac{2}{3} (\nabla \cdot U)^2 \right)^{0.5} \tag{4}$$

Meanwhile, in Deardorff model, the turbulence viscosity is able to be decided as below with the subgrid-scale kinetic energy (k_{sgs}) [15]:

$$\mu_t = \rho C_v \Delta \sqrt{k_{sgs}} \tag{5}$$

$$k_{sgs} = \frac{1}{2} \left((\overline{u} - \overline{\widehat{u}})^2 + (\overline{v} - \overline{\widehat{v}})^2 + (\overline{w} - \overline{\widehat{w}})^2 \right) \tag{6}$$

Other relevant parameters omitted in the above equations are

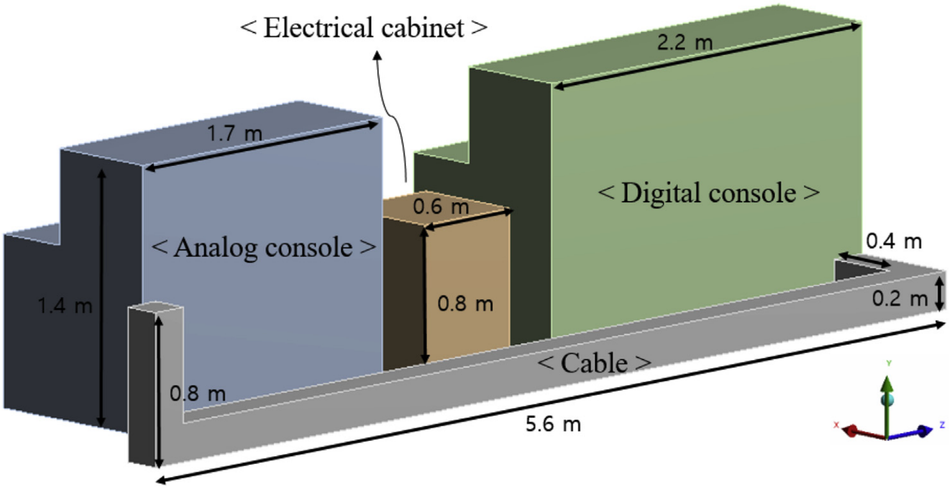


Fig. 1. Schematic of control room in AGN educational reactor.

Table 1
Analysis cases for thermal integrity evaluation.

Smagorinsky model			Deardorff model		
Case	Ignition source	Cable	Case	Ignition source	Cable
S1	Electrical cabinet	PVC	D1	Electrical cabinet	PVC
S2	Analog console		D2	Analog console	
S3	Electrical cabinet & Analog console		D3	Electrical cabinet & Analog console	
S4	Electrical cabinet	XLPE	D4	Electrical cabinet	XLPE
S5	Analog console		D5	Analog console	
S6	Electrical cabinet & Analog console		D6	Electrical cabinet & Analog console	
S7	Electrical cabinet	PVC	D7	Electrical cabinet	PVC
S8	Analog console		D8	Analog console	
S9	Electrical cabinet & Analog console		D9	Electrical cabinet & Analog console	
S10	Electrical cabinet	XLPE	D10	Electrical cabinet	XLPE
S11	Analog console		D11	Analog console	
S12	Electrical cabinet & Analog console		D12	Electrical cabinet & Analog console	

* Case S1 ~ S6 & D1 ~ D6: Ventilation condition of 0.67 m^3/s.
* Case S7 ~ S12 & D7 ~ D12: Ventilation condition of 0.33 m^3/s.

Table 2
Analysis cases for structural integrity evaluation.

Case	Ignition source	Case	Ignition source
I1	Electrical cabinet	I4	Electrical cabinet
I2	Analog console	I5	Analog console
I3	Electrical cabinet & Analog console	I6	Electrical cabinet & Analog console

* Case I1 ~ I3: Ventilation 0.67 m^3/s.
* Case I4 ~ I6: Ventilation 0.33 m^3/s.
* Structural analyses were implemented with Smagorinsky model.

delineated in nomenclature of this manuscript and effects of the difference will be discussed in analysis results and discussion parts.

2.3. Analysis models and methods

Two kinds of analysis models were developed by using FDS (Fire Dynamics Simulator) and ANSYS (ANalysis System). With regard to the former software, which was employed in main thermal analyses, trustworthy results can be obtained when the ratio of fire's characteristic diameter (D^*) in Eq. (7) and size of a grid belongs to a value between five and ten [5]. Grid sensitivity analyses were performed and the preceding ratio with ignition sources was set to approximately median value of verified ones. Thereby, the uniformly distributed optimum size was determined as 0.1 m taking into account computational efficiency and accuracy. As boundary conditions, bottom sides of equipment as well as the connection between cable and digital console were fully fixed. Structural analysis is irrelevant to FDS.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \tag{7}$$

Supplementary CFD models were also constructed by the latter, in more specifically, ANSYS CFX. Hexahedral mesh was generated and numbers of cells consisting the cable, analog console, digital console and electrical cabinet were the same with those of FDS as

264, 2040, 2640, 288, respectively. Region of air was divided by 95095 cells that are almost same to 92808 cells in FDS. The skewness as a primary quality measure of mesh defined by Eq. (8) [21] was checked as good. Finite element (FE) models for structural analyses were made by its Mechanical module [22].

$$\text{Skewness} = \max\left[\frac{\theta_{max} - \theta_e}{180 - \theta_e}, \frac{\theta_{min}}{\theta_e}\right] \tag{8}$$

Table 3 summarizes thermal properties of cables used in fire simulation, and is cited in a regulatory guideline [5]. Both PVC and XLPE were considered as representative thermoplastic and thermoset materials, respectively. As specific damage criteria of the PVC cable, the temperature of 205 °C and heat flux of 6 kW/m^2 were taken from NUREG-6850 [19]. Similarly, damage criteria of the XLPE cable were determined as the higher temperature of 330 °C and heat flux of 11 kW/m^2. It was conservatively assumed that integrity of the cable is lost if thermal analysis data exceed these criteria within the operators' reaction time of 300 s.

In the meantime, material properties of the steel having a carbon component of 0.3 wt% or less were referred for the electrical cabinet and operating consoles. Temperature dependent generic data such as elastic moduli of 201–203 GPa and a constant Poisson's ratio of 0.3 [23,24] were adopted. Relevant damage criterion was simply set to the yield strength and used for determination of integrity of the digital console by comparing with von Mises stresses obtained from elastic structural analyses.

3. Results and discussion

3.1. Thermal integrity evaluation

As indicated in Table 1, twenty-four sets of thermal analysis data were generated by FDS and compared each other. When the ventilation conditions increased as double, the results calculated under 0.67 m^3/s were more conservative than those under 0.33 m^3/s as expected. From the location of ignition sources standpoint, the maximum temperature and heat flux histories of the cable in the concurrent fires like S3, S6, S9, S12, D3, D6, D9, D12 were overall higher than others. Further, in these eight cases, contribution of the electrical cabinet fires was greater than that of the analog console fires. The reason is to be explained in the following section together with the results of structural analyses.

Fig. 2 shows effect of two turbulent models proposed by Smagorinsky and Deardorff, in which S4 and D4 are compared as representative examples. The results of case D4 were 1.25% higher in the maximum temperature and 9.83% higher in the maximum heat flux than each of them in case S4. Moreover, the maximum temperature of case D1 was 6.86% higher than that of case S1 while those were similar between cases D10 and S10. The maximum heat fluxes of cases D1 and D10 were also 5.24 and 7.95% higher than those of cases S1 and S10, respectively. These varying results are due to the difference in the turbulence viscosity between two models as well as specific analysis conditions.

Fig. 3 depicts effect of two cable materials focused on the maximum temperature histories in the analog console fires. As representative examples, the value of case D8 using thermoplastic

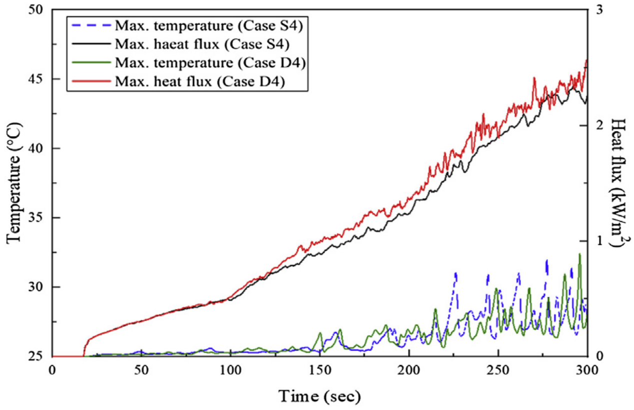


Fig. 2. Maximum temperature and heat flux histories according to turbulence models.

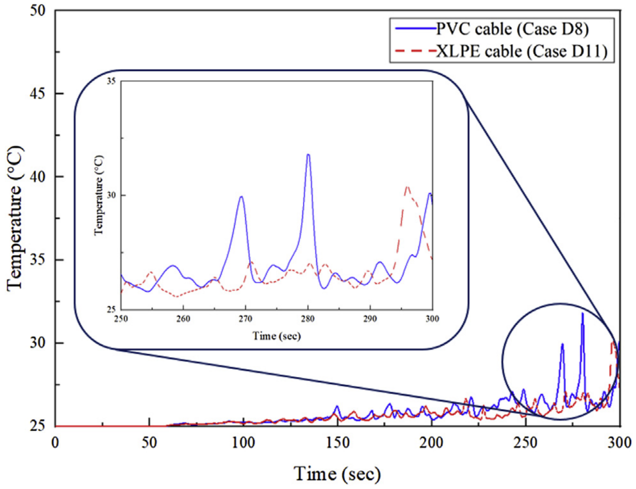


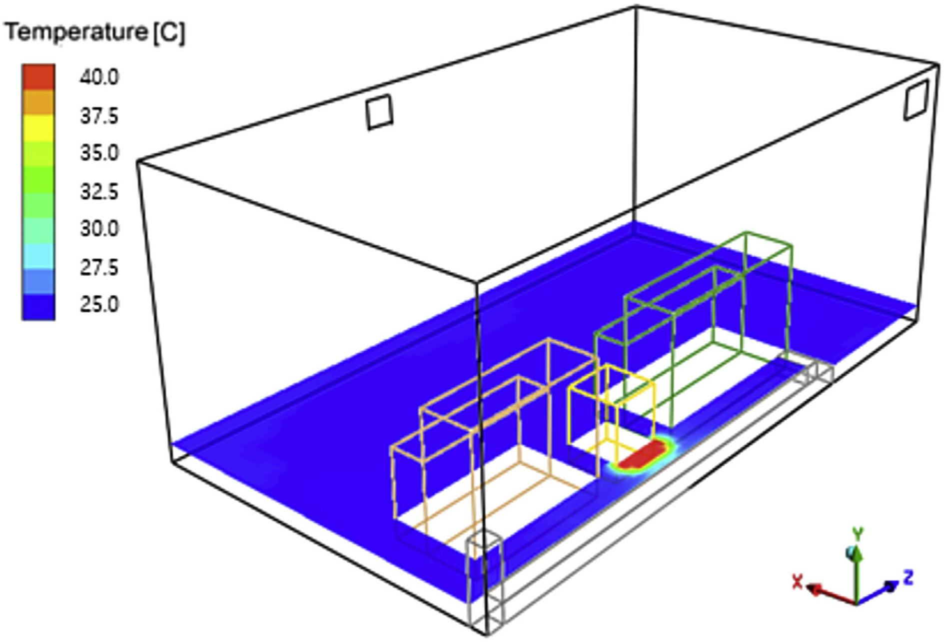
Fig. 3. Maximum temperature histories according to cable types.

PVC was 4.61% higher than that of case D11 using thermoset XLPE. Similarly, the value of case D2 was 4.40% higher than that of case D5 and the value of case S2 was 5.20% higher than that of case S5. In the electrical cable fires, the mean value averaging maximum temperatures of thermoplastic PVC cables (S1, S7, D1 and D7) was 4.35% higher than that of thermoset XLPE cables (S4, S10, D4 and D10). These distinct features depended on reciprocal influence of more governing parameter either the specific heat or thermal conductivity.

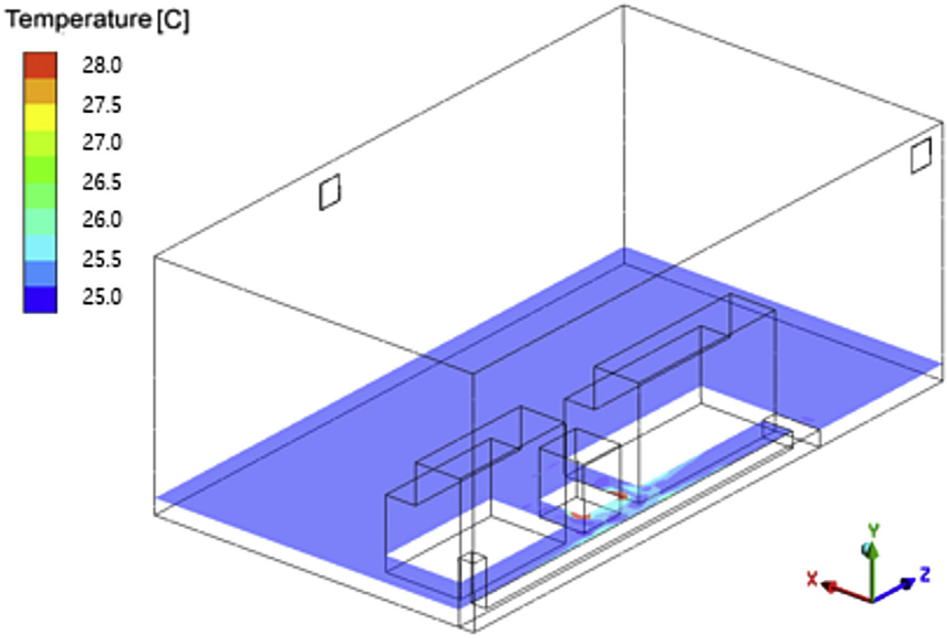
Twelve supplementary thermal analysis results by ANSYS CFX with the Smagorinsky turbulence model were compared with the corresponding cases S1~S12 by FDS. Overall, FDS provided conservative results such as 1.27 times higher maximum temperature in case S3 for instance. Fig. 4 compares temperature distributions of case S7, obtained from two softwares, at the section of 0.2 m height equivalent to the top surface of cable. Whereas temperatures were high near the ignition source of electrical cabinet, the values and

Table 3
Thermal properties of cables used in fire simulation [5].

Material	Thermal conductivity (W/m-°C)	Specific heat (kJ/kg-°C)	Density (kg/m^3)
PVC	0.192	1.289	1380
XLPE	0.235	1.390	1375



(a) FDS

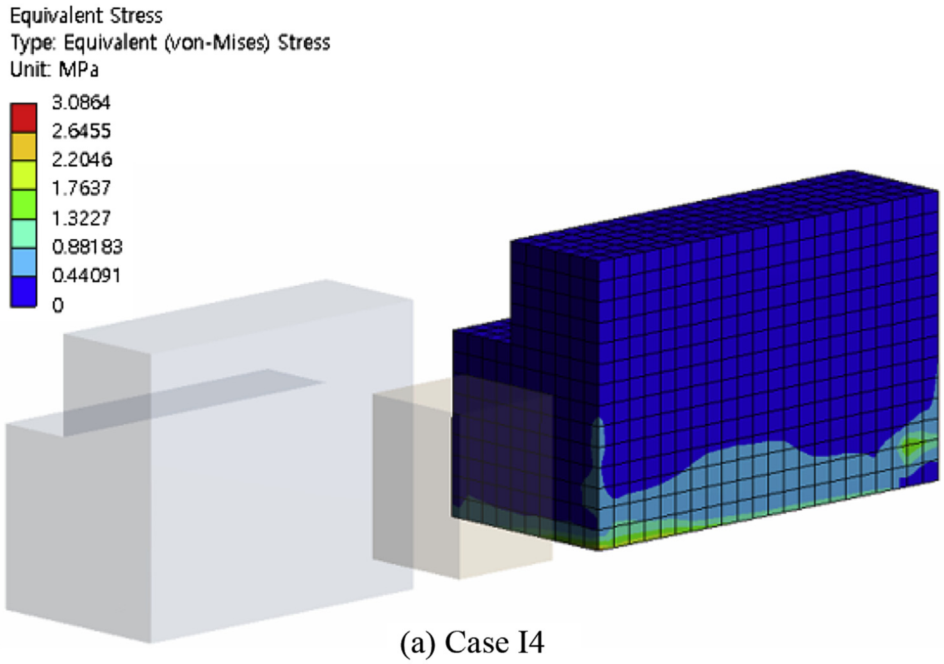


(b) ANSYS

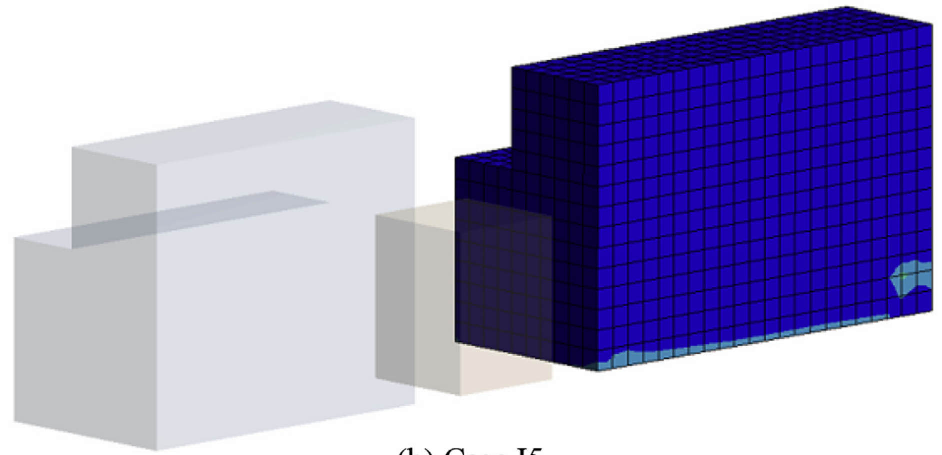
Fig. 4. Sectional temperature distributions of case S7 at 300 s.

Table 4
Verification of key parameters based on thermal analysis results of the AGN reactor.

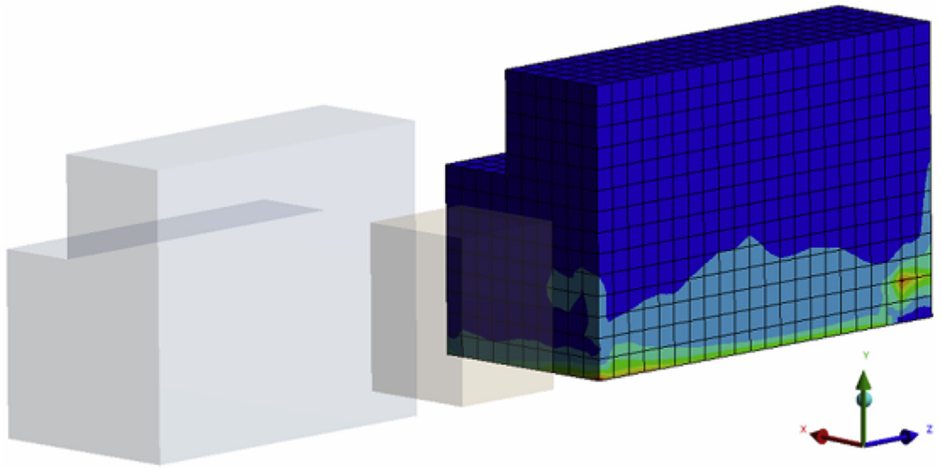
Parameter	Electrical cabinet	Analog console	Valid range
Fire Froude number ($\dot{Q}^*$)	0.77	0.16	0.4–2.4
Flame length ratio ($\frac{H_f + L_f}{H_c}$)	0.87	0.80	0.2–1.0
Equivalence ratio (ϕ)	0.19	0.29	0.04–0.6
Compartment aspect ratio ($\frac{L}{H_C}$)	2.53	2.53	0.6–5.7
Radial distance ratio ($\frac{r}{D}$)	0.36	0.31	2.2–5.7



(a) Case I4



(b) Case I5



(c) Case I6

Fig. 5. von Mises stress distributions of digital operating console under 0.33 m^3/sec condition.

distributions were quite different. It was not easy for drawing out quantitative trend due to significant variation and the cause of deviation could not yet be clarified. As consequence of the thermal integrity evaluation, irrespective of analysis softwares, the cable connected to the digital console sustained its intended function within the operator's reaction time under all the postulated cases considered in this study.

3.2. Verification of thermal analysis results

In order to check applicability of fire models in FDS for the unique educational reactor, key parameters affecting thermal analyses were evaluated base on a report [25]. At first, the fire Froude number ($\dot{Q}^*$) can be determined as Eq. (9), in which the fire diameter (D) is calculated as Eq. (10).

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty C_P T_\infty D^2 \sqrt{gD}} \tag{9}$$

$$D = \sqrt{\frac{4A}{\pi}} \tag{10}$$

The flame length ratio can be also implemented as Eq. (11) and the flame height (L_f) is able to be analyzed as Eq. (12).

$$Flame\ \ length\ \ ratio = \frac{H_f + L_f}{H_c} \tag{11}$$

$$\frac{L_f}{D} = 3.7\dot{Q}^{*2/5} - 1.02 \tag{12}$$

The equivalence ratio (ϕ) can be determined as Eq. (13) in terms of the mass flow rate of oxygen into the enclosure ($\dot{m}_{o_2}$) with the volumetric flow rate of air into the enclosure ($\dot{V}$). Finally, the compartment aspect ratio is calculated as L/H_C and the radial distance ratio is determined as r/D. As mentioned previously, parameters in the above equations were delineated in nomenclature.

$$\phi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{o_2}} \tag{13}$$

$$\dot{m}_{o_2} = 0.23 \rho_\infty \dot{V} \tag{14}$$

Table 4 represents verification of the key parameters based on thermal analysis results of the AGN reactor according to ignition sources. As compared in the table, most parameters relating to thermal analyses were adequate. Only the fire Froude number in analog console and the radial distance ratios in both analog console and electrical cabinet were deviated from the valid range. These seems to be affected by educational reactor specific space and equipment arrangement, which acted as a cause of the aforementioned difference with CFX results due to significant dependency on the heat fluxes.

3.3. Structural integrity evaluation

Temperature profiles obtained by CFX with Smagorinsky model were used as input for elastic structural analyses of the digital operating console by ANSYS Mechanical. Fig. 5 depicts resulting von Mises stress distributions under the ventilation condition of 0.33 m^3/s. In case I4, the maximum stress observed at the lower surface close to the electrical cabinet as an ignition source. Stresses were concentrated at the connection between cable and digital console in case I5, and the maximum stress occurred at the lower area close to the electrical cabinet in case I6. In this figure, overall stress distribution was the lowest in case I5 since the electrical cabinet had a role of interfering with the fire. Trends of each case were similar to those of I1~I3 under the increased ventilation condition of 0.67 m^3/s.

Table 5
Comparison of maximum von Mises stresses in the digital console.

Case	von Mises stress (MPa)	Case	von Mises stress (MPa)
I1	2.68	I4	2.67
I2	1.23	I5	1.03
I3	4.00	I6	3.09

Table 5 summarizes the maximum von Mises stresses obtained from the six cases in Table 2. As expected, not only the highest values were observed in the concurrent fires like I3 and I6 but also the effect of ventilation was more significant. The values in the electrical cabinet fires of cases I1 and I4 were 2.18–2.59 times higher than the those in cases I2 and I5. It can be interpreted that the electrical cabinet was dominant comparing to the analog console because of the relatively close distance between ignition source and target in spite of relatively lower heat release rate. While the results of 0.67 m^3/s were higher than those of 0.33 m^3/s, effect of ventilation conditions was not significant or negligible in the electrical fires than expected. On the whole, the digital console sustained integrity within the operator's reaction time under all the considered postulated cases.

4. Discussion

Differences of simulated temperatures and heat fluxes were examined to show effects of considered fire scenarios, turbulence models, cable materials and ventilation conditions. Furthermore, the reason why temperatures and heat fluxes obtained by FDS were higher than the ANSYS CFX values was investigated. It is likely that the radial distance ratio calculated by using the distance between ignition source and target was out of the valid range as summarized in Table 4. The verification check was performed and ANSYS seems to be an alternative to resolve this limitation. While the current study was concentrated on the control room fires caused by electrical defects, consecutive studies are being prepared not only for other scenarios such as reactor room fire by oil ignition source but also for fitness-for-service evaluation of the reactor and facilities. When these numerical analyses are completed, further rigorous technical bases needed for advanced contingency planning, fire suppression strategy and corrective actions will be available.

5. Conclusions

In this study, electrical fire simulation of an AGN educational reactor was performed in the control room to examine numerical analysis parameters and conditions, and integrity of digital console. The following conclusions were obtained based on total of forty-two sets of thermal and structural analyses data, derived from three postulated scenarios, which met the allowable criteria.

(1) The mean values averaging differences of the maximum temperatures and heat fluxes were 2.36% and 7.69%, respectively, between cases S1, S4, S10 and D1, D4, D10. It can be recognized that the Deardorff turbulence model was more conservative than the Smagorinsky model.

(2) The mean value of the maximum temperature of thermoplastic PVC cables (S1, S7, D1 and D7) was 4.35% higher than

that of thermoset XLPE cables (S4, S10, D4 and D10). It means that the PVC cable was more vulnerable than XLPE cable.

(3) While temperatures and heat fluxes increased as the ventilation volume became double, the influence was not significant than expected. FDS provided also relatively conservative thermal analysis results, however, it was not easy for drawing out quantitative trend due to significant variation and the cause of deviation could not be clarified.

(4) The von Mises stress in the electrical cabinet fires of cases I1 and I4 were 2.18–2.59 times higher than the those in cases I2 and I5. It can be interpreted that, although the heat release rate of an analog console was higher than those of electrical cabinet, the electrical cabinet was more dominant due to close distance between ignition source and target.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

A: Plan area of the burning fuel (m^2)
c_p: Specific heat (kJ/kg-°C)
C_s: Smagorinsky coefficient (−)
C_v: Deardorff coefficient (−)
D: Fire diameter (m)
D^*: Fire’s characteristic diameter (−)
g: Acceleration of gravity (m/s^2)
H_c: Enclosure height (m)
H_f: Base height of the fire (m)
ΔH_{O_2}: Heat of combustion for oxygen (kJ/kg)
k_{sgs}: Subgrid-scale kinetic energy (−)
k_t: Thermal conductivity (W/m-°C)
L: Compartment length (m)
L_f: Flame height (m)
$\dot{m}_{O_2}$: Mass flow rate of oxygen into the enclosure (kg/s)
Pr_t: Turbulent Prandtl number (−)
$\dot{Q}$: Fire heat release rate (kW)
$\dot{Q}^*$: Fire Froude number (−)
r: Actual distance between the target and the center of the fire base (m)
$|S|$: Strain rate scalar (−)
S_{ij}: Strain tensor (−)
Sc_t: Turbulent Schmidt number (−)
T_∞: Ambient air temperature (K)
U: Velocity vector (−)
u, v, w: Component of velocity vector (−)
$\overline{u}, \overline{v}, \overline{w}$: Average value of u, v, w at the grid center (−)
$\widehat{\overline{u}}, \widehat{\overline{v}}, \widehat{\overline{w}}$: Weighted average of u, v, w over the adjacent cells (−)
$\dot{V}$: Volumetric flow rate of air into the enclosure (m^3/s)
Δ: LES (Large Eddy Simulation) filter width (−)
μ_t: Turbulence viscosity (m^2/s)
$\theta_{max}, \theta_{min}$: Largest angle in the cell, Smallest angle in the face (rad)
θ_e: Angle for an equiangular cell (rad)
ρ: Air density (kg/m^3)
$(\rho D)_t$: Mass diffusivity (m^2/s)
ϕ: Equivalence ratio (−)