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Research Article

Modified Fire Simulation Curve of Cabin Temperatures in Postcrash Fires for Fire Safety Engineering

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The fire simulation curve this paper presents is based on a curve which is proposed by Barnett in 2002. The curve is used to study the temperature change in a fire scenario in the interior of a rectangular compartment. However, it is not applicable to use in some long, limited spaces with arc boundaries, such as aircraft cabins. Some improvements and simplifications are made to the curve to solve this problem. A numerical simulation is conducted via the modified curve in a B737 fuselage during a postcrash fire. The result is compared with a fire dynamics simulator (FDS) simulation and a full-scale test undertaken by the National Aeronautics and Space Administration (NASA). The practicability and accuracy of the modified curve is proved through the relevant analysis and the main relative error analysis. The time to flashover is also predicted by the curve and the FDS simulation, respectively. Several parameters are chosen as influence factors to study their effect on the time to flashover in order to delay the occurrence of the flashover. This study may provide a technical support for the cabin fire safety design, safety management, and fire safety engineering.

1. Introduction

Aircraft cabin fires generally belong to one of the following three groups: ramp fires, in-flight fires, and postcrash fires [1]. Ramp fires do not generally threaten life. They usually occur when the aircraft is parked and unattended. In-flight fires mostly occur in accessible areas such as a galley or toilet and generally pose a slight threat to the safety of the passengers due to the quick detection and extinguishing of them before they develop into life-threatening situations. Postcrash fires are the most deadly type, and they mainly occur because of a collision with another object on the ground or the aircraft hitting the ground during takeoff or landing at a high speed. Fuel spilled from damaged pipes or ruptured fuel cells are ignited by coming into contact with hot engine components after the crash. Then the flames spread into the cabin through the broken fuselage or an open exit, leading to combustion of the interior combustibles. Postcrash fires occur frequently compared with the other two types of fires, and the consequences are the most deadly, as the aircraft is full of passengers. The passengers have difficulty surviving in the severe environment, especially after flashover occurs. As the temperature can directly affect the time to flashover during postcrash fires, it is meaningful to study the temperature change in the aircraft cabin to ensure passenger safety during emergency evacuation.

For many years, a series of full-scale fire tests have been undertaken by the Federal Aviation Administration (FAA) to study the temperature and the toxic gas conditions in postcrash fires using a C-133 fuselage. These tests addressed the postcrash scenario by considering a large external fuel-pool fire adjacent to an open cabin door. Various data concerning temperature, heat, and gas were collected, and the effects of the external ambient wind conditions, the pool size, and the door openings were examined. Real fire scenes inside the cabin after a crash were simulated, and these tests also confirmed the time to flashover [2–4]. The hazards of an enclosure fire, such as a fire inside the aircraft cabin, were grouped into three categories: heat, visibility, and toxic gases [5]. As a full-scale fire test takes a lot of time and money and it is impossible to obtain data from different fire scenarios, a main method of studying cabin fires is the use of field simulation based on computational fluid dynamics (CFD). In a recent application of fire field modeling [6, 7], Jia et al. used the CFD fire simulation software SMARTFIRE to assist the Transportation Safety Board (TSB) of Canada Fire and Explosion Group in their investigation of the Swissair MD-11 in-flight fire that resulted in the loss of the aircraft and all passengers and crew members. Wang et al. rebuilt the fire scene in a C-133 aircraft, using SMARTFIRE to predict the temperature change and the time to flashover for different types of materials [5]. The fire dynamics simulator (FDS) model was established by the graphical model appliance PyroSim by Zhang et al., and the differences in the temperature change between two scenarios, with a door opened and a door closed, were discussed [8]. Ji utilized the temperature data of an A380 aircraft cabin gained though FDS simulation compared with a model of human temperature and toxic gas endurance to obtain the available safe egress time (ASET). Then an emergency evacuation was simulated to determine the required safe egress time (REST) via Pathfinder, and an analysis was conducted to verify the personal safety of the evacuation procedure [9]. It required a great deal of time to establish the model of the cabin and to run the CFD software. Meanwhile, the boundary condition of the model was required to be very rigorous. Therefore, a parameter model that can be chosen to conduct a numerical simulation is more convenient at this time. ISO834, BS476, ASTM119, and NFPA251 [10–12] are the common parameter models, and the curve which is named BFD curve by Barnett is also a good choice, as proposed by Barnett [13].

All kinds of parameter models, however, conduct a numerical simulation of the indoor temperature based on a fire that occurs in the interior of a rectangular building, but they are not applicable for using in some limited spaces with arc boundaries, such as long, narrow tunnels and aircraft cabins. Therefore, some improvements and simplifications have been made to the curve to make it suitable for a numerical fire simulation within the limited space of the arc boundary to solve this problem. A numerical simulation of the interior temperature in a postcrash fire is conducted via the modified BFD curve using a B737 fuselage. An FDS model of the cabin is established by replacing the arc with a rotated rectangle via PyroSim. The temperature curves of the cabin, obtained from the modified BFD curve and the FDS simulation, are compared with data from full-scale fire tests undertaken by the National Aeronautics and Space Administration (NASA). The relevant analysis and the main relative error analysis are conducted to verify the feasibility and effectiveness of the improved parameter model. The time to flashover is also predicted. An analysis is conducted to study the factors influencing the time to flashover by changing the corresponding parameters according to the BFD curve and the FDS simulation. This study provides not only technical support for cabin fire safety design and safety management but also new thinking on numerical simulation in some limited spaces with arc boundaries. Meanwhile, the study of the influence factors of flashover can also be applied to delay the occurrence of flashover within fire scenarios.

2. Proposal of the Modified BFD Curve

2.1. Basic BFD Curve. The BFD curve is an experiential model based on Newton's law of cooling. It was presented by Barnett in 2002 after an analysis of abundant tests of room fires [13]. It is a curve that sets the burning time as the independent variable and the room temperature as the dependent variable. The basic equation that produces a BFD curve is as follows:

$$T = T_a + T_m e^{-z}, \quad z = \frac{(\ln t - \ln t_m)^2}{s_c}, \tag{1}$$

where T is the temperature at any time t (°C), T_a is the ambient temperature (°C), T_m is the maximum temperature generated above T_a (°C), t is the time from the ignition of a fire (min), t_m is the time at which T_m occurs (min), and s_c is the shape constant for the temperature-time curve.

The simplest method to calculate T_m was presented by Law and O'Brien [14] and uses the inverse opening factor $\eta = 1/F_{O2}$ ($m^{0.67}$) and the fire load mass density Ψ (kg/m^2) as follows:

$$T_m = 6000 \left[\frac{(1 - e^{-0.1\eta})}{\eta^{1/2}} \right] (1 - e^{-0.05\Psi}), \tag{2}$$

$$F_{O2} = \frac{(A_V h_V)^{1/2}}{A_{T2}}, \tag{3}$$

$$\Psi = \frac{B}{(A_V A_{T2})^{1/2}}, \tag{4}$$

where A_V is the sum of the areas of vertical openings, h_V is the weighted mean height of vertical openings, A_{T2} is the internal surface area less openings, and B is the total combustible mass fire load in wood equivalents (the combustion heat of wood is 13 MJ/kg).

The value of t_m for a fuel-surface controlled fire can be calculated as follows if one assumes that the values for the total fire load energy E and the two coefficients t_g^* and t_d^* are determined.

$$t_m = t_g^* \left(\frac{3E}{t_g^* + t_d^*} \right)^{1/3}, \tag{5}$$

where t_g^* is the growth coefficient, t_d^* is the decay coefficient, and the value depends on the speed of the fire growth and recession. Moreover, t_d^* is commonly 3 to 5 times the amount of t_g^* [13].

t_g^* is the time that heat release rate of the fire resource reaches 1 MW for a typical t^2 fire, which can be divided into several types (see Table 1).

The shape constant of the BFD curve is determined by the thermal insulation performance of the room. For uninsulated fire compartments,

$$s_c = \frac{1}{(4F_{O2} + 0.1)}. \tag{6}$$

Table 1: Different types of t_g^* for a typical t^2 fire.

Classification	Time t_g^* to reach 1 MW (s)
Ultra-fast	75
Fast	150
Medium	300
Slow	600
Ultra-slow	1200

For insulated fire compartments,

$$s_c = \frac{1}{(9.25F_{O2} + 0.21)}. \quad (7)$$

2.2. Improvements and Simplifications for the BFD Curve Based on Arc Boundaries. Since the BFD curve permits a algebraic expression for fire in the interior of a rectangular construction but is not applicable for spaces such as narrow tunnels and aircraft cabins, some improvements and simplifications should be made to fit these situations. Thus, some improvements and simplifications should be made to fit these situations. The total area can be estimated using an equal algorithm that calculates the equivalent width, replacing the original width by treating the cabin arc as a rectangle, as shown below:

$$A_{T2} = 2\left(LW^* + LH + W^*H\right) - A_V, \quad (8)$$

where L is the length of the cabin, H is the height of the cabin, and W^* is the equivalent width of the cabin, which is calculated via the equal algorithm.

Research has shown that the maximum temperature should be increased by 10% based on (2) for adiabatic space, but the result should not exceed 1,250°C [13]. Therefore, (2) is modified according to the smaller value for the opening factor F_{O2}.

Take $(1-e^{-0.05\Psi}) \approx 1$ into $T_m = 6000[(1-e^{-0.1\eta})/\eta^{1/2}](1-e^{-0.05\Psi})$ and multiply 110%:

$$T_m = \frac{6600\left(1 - e^{-0.05\Psi}\right)}{\eta^{1/2}}. \quad (9)$$

As the fire is located at the breakage of the cabin and derived from the pool fire produced by aviation kerosene, abundant air is provided to the fire. Meanwhile, the cabin space is very large, and there is sufficient air supporting the combustion of the internal combustibles, though the ventilation area rate is rather low. Thus, the postcrash fire can be considered a fuel-controlling fire rather than a vent-controlling fire. If t_d^* takes 4 times the size of t_g^*, the equation calculating t_m could be simplified for the cabin as follows:

Take $t_d^* = 4t_g^*$ into $t_m = t_g^*(3E/(t_g^*+t_d^*))^{1/3}$ (Equation (5)):

$$t_m = \left(\frac{3}{5}\right)^{1/3} E^{1/3} t_g^{*2/3}. \quad (10)$$

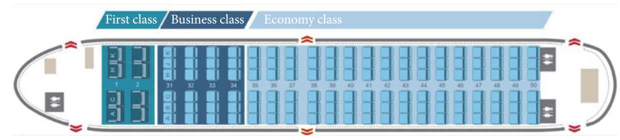

Figure 1: Structure chart of a B737 cabin.

3. Case Analysis on Accuracy of Modified BFD Curve

3.1. Model Choosing and Scenario Setting. The B737 aircraft is a primary type of civil aviation transportation in China, and it is produced by the Boeing. More than 600 B737 aircrafts are currently in active service. Therefore, a B737 aircraft was chosen as simulation object. The cabin of a B737 aircraft is 23.26 m long, 3.75 m wide, and 2.3 m high. With a level 2 seat layout, eight seats are arranged in first class, 24 seats are in business class, and 96 seats are in economy class, for a total of 128 seats in the cabin, as shown in Figure 1.

As the influence of the ventilation in the cabin is obvious in the fire scene [15], so the choice of the opening exit is directly related to the accuracy of the simulation results. Xu's study showed that the probability is very small that two doors cannot be opened at the same time among each group exits (8%, 8%, and 25%, resp.), according to an analysis based on a large number of cases of evacuation during aircraft accidents [16]. The airworthiness standards for transport category airplanes require that 50% of the exits should be opened during the demonstration of evacuation procedures [17]. Thus, the opening model is set as a unilateral model combining the probability distribution of exits being opened in accordance with the regulatory requirements. The numerical simulation is carried out with two exits on the right side chosen as opening exits. At the same time, the central emergency exit cannot be opened due to high temperature.

The simulation scenario is set based on the characteristics of postcrash aircraft fires. It is supposed that the fuselage is broken and leaned to left after the crash. The breakage is at the middle of the cabin near the emergency exit. All of the left exits and emergency exits are closed, and the size of the breakage is determined to be 1 m × 1.08 m, according to the full-scale test conducted by Galea et al. [18]. The leaked aviation kerosene is ignited by a blazing spark, and the flame begins to spread into the cabin from the breakage and causes burning of the combustibles in the cabin.

3.2. Numerical Simulation Based on FDS. The fire dynamics simulator (FDS) is used invariably to build rectangular boundary models, so a method of replacing the arc with a rotated rectangle is used to build the arc of the cabin via a visual modeling tool, PyroSim. The fire is set as a typical t^2-stability fire, located at the breakage of the cabin near the emergency exit. The heat release rate (HRR) of the fire is set at 10 MW according to the pool fire model of leaked jet fuel [19] and to attain its maximal value at 237 seconds. A thermocouple is set at 2.2 m in height from the floor to monitor the gas temperature change at the top layer, and the

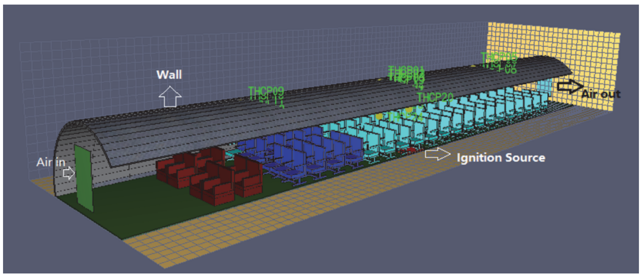

Figure 2: FDS model of a B-737 aircraft cabin.

grid size is set at 0.2 m × 0.2 m × 0.2 m, with a simulation time of 1,000 seconds. The FDS model is shown in Figure 2.

The material of the cabin and the baggage rack is defined as carbon fibre reinforced plastic (CFRP). The specific parameters are shown in Table 2.

Table 2: Combustion characteristics of the cabin material.

Category	Value
Density	116 kg/m^3
Conductivity	0.05 W/(m·K)
Specific heat	2.09 kJ/(kg·K)
Thickness	0.03 m
Heat release rate (HRR)	65 kW/m^2
Ignition temperature	505°C
Initial temperature of simulation space	20°C

3.3. Numerical Simulation Based on the Modified BFD Curve. T_m, t_m, and s_c are determined via the modified BFD curve for the cabin. The ambient temperature is set at 20°C, and the combustion heat of the seats, the carpet, and aviation kerosene is given as 20 MJ/kg, 22.3 MJ/kg, and 46.91 MJ/kg, respectively [20–22]. The total fire load mass is estimated using various fuels, and a numerical simulation is conducted using (1) to (10) and the relevant parameters. Each parameter needed in a BFD curve is shown in Table 3.

Table 3: Input data for the BFD curve.

Input data	Value
Total fire load energy E	40000 MJ
Length of the cabin L	23.26 m
Width of the cabin W	3.75 m
Height of the cabin H	2.3 m
Sum of areas of vertical openings A_V	4.6 m^2
Weighted mean height of vertical openings h_V	0.8 m
Fire growth coefficient t_g^*	75 s
Fire decay coefficient t_d^*	300 s

3.4. Results and Discussion

3.4.1. Modified BFD Curve for an Aircraft Cabin. A numerical fire simulation for a B737 aircraft cabin is conducted according to the modified BFD curve and the related input parameters. The value of each parameter in the modified BFD curve is calculated: $T_m = 803.3°\text{C}$, $t_m = 8.55\ \text{min} = 513\ \text{s}$, and $s_c = 2.85$. Therefore, the modified BFD curve in the postcrash fire is achieved as shown below.

Take $E = 4000$, $t_g^* = 75$ into $t_m = (3/5)^{1/3} E^{1/3} t_g^{*2/3}$ (10):

$$t_m = \left(\frac{3}{5}\right)^{1/3} \times 40000^{1/3} \times 75^{2/3} = 512.99 \approx 513,$$
$$T = 20 + 803.3 e^{-(\ln t - \ln 513)^2/2.85}. \tag{11}$$

This curve shows that the cabin temperature can reach 823.3°C for a maximum value in the B737 fuselage at 513 seconds after the aircraft crash.

3.4.2. FDS Simulation. According to the FDS model established above, multiple runs of the FDS simulation are conducted to ensure the accuracy of the simulation procedure, as the model involves some stochastic processes. Ten runs are considered a reasonable number because increasing the number of runs has little influence on the average temperature, as well as the maxima and the minima. The maximum temperatures and occurrence times for each run are calculated via the simulation, shown in Table 4.

The differences for maximum temperature and occurrence time among each runs are pretty small. And the mean values are chosen as a result of the temperature curve. The average maximum temperature is 847.8°C, which occurs at 550 s after the crash according to ten runs of the FDS simulation.

3.4.3. Full-Scale Fire Tests. NASA conducted a series of full-scale fire tests to support numerical fire simulation based on a B737 aircraft in 1982; data for nearly 3,000 curves were obtained. Test 24, reported in NASA Technical Memorandum 58244 [23], was selected as a comparison group to compare with the temperature curves achieved using the BFD curve and the FDS simulation. The full-scale fire tests use a square fuel pool of 0.61 m × 0.61 m with about 4.5 liters of JP-1 aviation kerosene in it to produce a pool fire, located in the midline of the cabin near the outer wall. The ventilation rate is 14.2 m^3/min, and the internal materials include covered urethane foam seats and walls, a power supply unit (PSU), bins, and ceiling panels. This full-scale fire test, however, shows that the maximum temperature can reach 810°C in the cabin and that it occurs at 470 s.

3.4.4. Accuracy Analysis for the Modified BFD Curve. To analyze the accuracy of the modified BFD curve, it is compared with the FDS simulation and the full-scale test undertaken by NASA. The comparison shows that the modified BFD curve is more accurate in determining the maximum temperature and its occurrence time than the FDS simulation in a long, narrow space with an arc boundary according to the data from these

Table 4: Statistics for the FDS simulation.

Runs	1	2	3	4	5	6	7	8	9	10
Maximum temperature/°C	848.0	847.2	850.1	849.0	842.8	848.7	851.3	847.2	849.2	844.5
Occurrence time/s	546.7	549.5	552.2	548.0	555.1	551.1	548.4	552.3	550.3	547.4

Table 5: MRE between the numerical simulation and NASA's test data compared with NASA's test.

Time (min)	0–2	2–4	4–6	6–8	8–10	10–12	12–14
MRE for FDS simulation	1.169	5.027	2.588	0.228	0.068	0.196	0.097
MRE for BFD curve	2.523	5.502	2.498	0.237	0.093	0.285	0.336

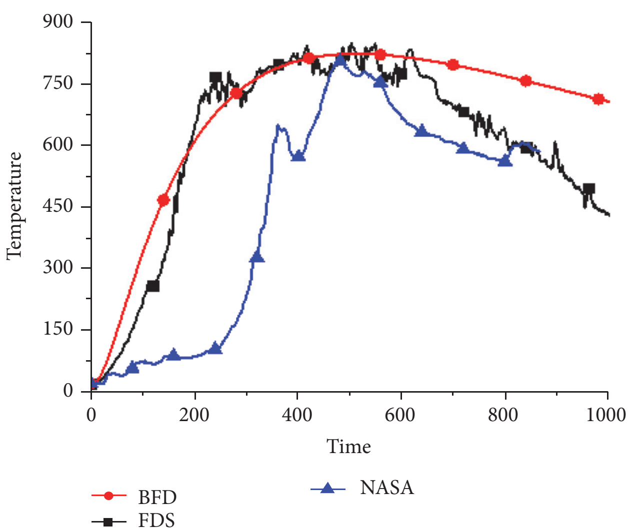

Figure 3: Cabin temperature curve.

two models. The cabin temperature curve of the BFD curve, the average temperature of the FDS simulation, and NASA's full-scale fire test are shown in Figure 3.

Figure 3 shows that the cabin temperature rises rapidly after the aircraft crash, according to the BFD curve and the FDS simulation model, and that the temperature can reach 600°C at around 200 s. However, the full-scale fire test undertaken by NASA shows that the temperature in the cabin rises flatly in the beginning, and it rises rapidly until 200 s. Then the flashover occurs, and combustibles in the cabin such as carpet and seat backs will ignite. The temperature continues to rise, and it reaches the maximum temperature of about 810°C at 470 s. As the combustibles burn out and the oxygen content drops gradually, the temperature also declines gradually.

In addition, the cabin temperature data obtained though the BFD curve and the FDS simulation trend are very similar to those of NASA's test, and there is only about 100 seconds' delay in the heating speed compared with NASA's test because the fire resource is not a normal ideal t^2 fire in a real environment. During the growth stage of the fire (600 seconds before), the BFD curve is rather close to the FDS curve, with a difference of no more than 100°C. The three curves reach the maximum temperature at the same time, about 500 seconds after ignition. However, during the decay stage of the fire (600 seconds to 1,000 seconds), a separation appears gradually between the BFD curve and the other two curves in that the decline in the temperature for the BFD curve is relatively flat, while the cabin temperatures of NASA's test and the FDS simulation drop rapidly. The temperature difference between the BFD curve and the FDS simulation may exceed 270°C at 1,000 seconds because the combustibles in the cabin have been fully burned. The data gained from the BFD curve and the FDS simulation are compared with NASA's full-scale fire test according to the correlation coefficient analysis. The correlation coefficient can be calculated using the equation below:

$$r = \frac{\left(n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i\right)}{\sqrt{\left[n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2\right]\left[n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2\right]}}. \quad (12)$$

The equation shows that the closer the correlation coefficient r is to 1, the higher the similarity of the two samples is. The statistical software Excel is used to compute the correlation coefficient. The sample size n is 500 and the time interval for each data is 2 seconds. The correlation coefficient $r = 0.725$ is obtained for the FDS curve and the experimental data, and it is moderate positive correlation because the correlation coefficient is between 0.8 and 0.5. The correlation coefficient between the BFD curve and NASA's experimental data is $r = 0.800$, which is a highly positive correlation. This indicates that the FDS simulation and the BFD curve have trends that are quite similar to those of NASA's experimental data and that the BFD curve can reflect the trend of temperature change in a cabin fire better than the FDS simulation.

The main relative error (MRE) is a dimensionless numerical value that can be more valid than the absolute error for two groups of numerical value:

$$\text{MRE} = \sum_{i=1}^{n} \frac{1}{n}\left[\frac{(x_i - y_i)}{x_i}\right]. \quad (13)$$

The MRE between the numerical simulation and NASA's test data are calculated, respectively, using the statistical software Excel. The results are shown in Table 5.

Table 6: Influence of the time to flashover after increasing parameters by 10%.

	F_{O2}	E	t_g^*
Time to flashover (BFD)	186.4 s	200.2 s	207.8 s
Time difference	−8.2 s (−4.19%)	4.7 s (+2.40%)	12.3 s (+6.29%)
Time to flashover (FDS)	183.2 s	187.0 s	198.5 s
Time difference	−6.2 s (−3.27%)	−2.4 s (−1.26%)	9.1 s (+4.80%)

As shown in Table 5, the main error between the numerical simulation and the data from NASA's test occurs in the first 6 minutes, during the growth stage of the fire. This is caused by the slow rise of the temperature in NASA's test beginning at 200 seconds, but the FDS simulation and BFD curves rise rapidly after ignition because of the normal ideal t^2 fire setting, while the real test is not a normal ideal setting. The temperature difference between the numerical simulation and the test data is rather small in the steady stage of the fire, especially from 10 min to 12 min, as the error is less than 10% for both the FDS simulation and the BFD curve. In general, the BFD curve exactly reflects the temperature change in the cabin fire, except for a small defect in the later stage, compared with the FDS simulation.

4. Application of the Modified BFD Curve in Analyzing Flashover

Flashover occurs when a fire changes into an overall fire from a local fire, and all the combustible indoor surfaces begin to burn after this change. The people in the fire scene are unlikely to survive due to a dramatic increase in the temperature and the concentration of toxic gas, as well as the quick decrease in visibility after flashover occurs. Therefore, the prediction of time to flashover and the study of influential factors are very important for passenger safety during the evacuation when an aircraft catches fire. According to the criteria for judging a flashover proposed by McCaffrey et al. [24], a flashover may occur when the gas temperature in the upper layer reaches 600°C or the surface heat flux on the floor is more than 20 kW/m^2.

Through the numerical simulation of the BFD curve for a cabin fire, we use T_m = 580°C in (11), and the time to flashover obtained is 195.5 s, while the time to flashover simulated via FDS is 189.4 s. Meanwhile, NASA's experimental data shows that the flashover happened in the cabin at 350.2 s, with about a 150-second delay compared with prediction obtained using the modified BFD curve and the FDS simulation, which is due to the different rate of temperature increase at the beginning of the fire. The opening factor F_{O2}, the total fire load energy E, and the fire growth coefficient t_g^* are increased by 10% each, leaving the other conditions unchanged to study how these parameters affect the time to flashover according to the calculated BFD curve and the established FDS model. The time to flashover is predicted under different scenarios, and some comparisons are conducted to analyze the influence on the flashover time after certain changes in different parameters compared with the original scenario.

As shown in Table 6, increasing the opening factor F_{O2} can make the flashover occur earlier. Both the increasing of the sum of the areas of vertical openings A_V and the weighted mean height of the vertical openings h_V could make the opening factor F_{O2} increase and lead to more oxygen getting into the cabin to support the burning of combustibles such as carpet and seat cushions. Then the combustion becomes more intense. The gas temperature in the top layer ascends more rapidly during the burning process, and the time to flashover becomes shorter as a result. Although increasing the total fire load energy E could increase the maximum temperature of the fire, it also can lead to a delay in reaching the maximum temperature, according to the BFD curve. In the FDS simulation, the total fire load energy E generally has little influence on the time to flashover. Furthermore, increasing the fire growth coefficient could greatly increase the time required to reach the maximum heat release rate of the fire, and the time to flashover will also be delayed substantially. Therefore, some methods are available to delay the time to flashover, and reducing the vent area or vent height may be good choices. Otherwise, increasing the time required to reach the maximum heat release rate of the fire can be another method to increase the time to flashover substantially.

5. Conclusion

Improvements and simplifications are made to the BFD curve to carry out a numerical fire simulation in a long, narrow space with an arc boundary. The temperature curves in the cabin obtained via a modified BFD curve and a FDS simulation during a postcrash fire are compared with the results of a full-scale fire test undertaken by NASA based on the B737 aircraft. The results show that the calculated BFD curve has a highly positive correlation with the experimental data, and the practicability and accuracy of using the modified BFD curve to conduct a numerical simulation of a cabin fire have been proved.

The cabin temperature data achieved through the BFD curve and the FDS simulation have trends very similar to those of NASA's test, with a delay of only about 100 seconds in the heating speed compared with NASA's test. The temperature difference between BFD curve and test data is rather small in the steady stage of the fire, especially in 10 min to 12 min, where the MRE is less than 10%. In general, BFD curve reflects the temperature change in the cabin fire exactly, except a small defect in the later stage compared with FDS simulation.

According to BFD curve, the cabin temperature can reach a maximum value of 823.3°C in a B737 fuselage 513 s after a crash, and the time to flashover is predicted to be 195.5 s. The time to flashover can be delayed by reducing the opening factor F_{O2} or increasing the fire growth coefficient t_g^*. In addition, total fire load energy E generally has little influence on the time to flashover.

It is too expensive and difficult to conduct a full-scale fire experiment involving a postcrash fire. A corresponding fire receptor model is also needed to establish the value of using the FDS simulation, which needs a very harsh boundary condition for the computation. However, the input parameters needed for the BFD curve are simple and clear, and the results of the numerical simulation are rather accurate, especially for predicting the maximum temperature and the time at which it happened. The BFD curve can be used for aircraft cabins and other long, narrow spaces with arc boundaries after the improvements and simplifications made in the study. In addition, knowledge of how to modify the BFD curve to improve its accuracy in the fire growth stage is still needed to be obtained in further research.

Nomenclature

A_{T2}: Internal surface area less openings, m^2
A_V: Sum of areas of vertical openings, m^2
B: Total combustible mass fire load in wood equivalents, kg
E: Total fire load energy, MJ
F_{O2}: Opening factor, $m^{1.5}$
H: Height of the cabin, m
h_V: Weighted mean height of vertical openings, m
L: Length of the cabin, m
r: Correlation coefficient, dimensionless numbers
s_c: Shape constant for the temperature-time curve, dimensionless numbers
T: Temperature at any time t, °C
T_a: Ambient temperature, °C
T_m: Maximum temperature generated above T_a, °C
t: Time from ignition of fire, min
t_d^*: Fire decay coefficient, s
t_g^*: Fire growth coefficient, $m^{0.67}$
t_m: Time at which T_m occurs, min
W^*: Equivalent width of the cabin, m
Ψ: Fire load mass density, kg/m^2
η: Inverse opening factor, $m^{0.67}$.

Competing Interests

The authors declare that they have no competing interests.

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