AN EVALUATION OF THE BFD CURVE BASED UPON WOOD CRIB FIRES PERFORMED IN AN ISO9705 ROOM

by

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The BFD curve fitting method of Barnett is adopted to study the compartment temperature-time curves for a series of wood crib fires in an ISO 9705 room. The nominal fire sizes were 0.15 MW, 0.25 MW, 0.5 MW, and 1.0 MW. The cribs were positioned at the corner or the center of the floor of the room. The temperatures within the compartment were measured using two thermocouple trees with 10 thermocouples on each tree; these measured the compartment temperature from floor to ceiling. No flashover occurred during the tests, and the compartment temperature can be well described by a two-zone model. BFD curve fitting was performed for all 20 temperature-time curves in the upper and lower zones of the compartment for each test. The fitting error is evaluated for all tests. This empirical model needs more tests to verify and optimize.

Key words: *compartment temperature, wood crib fire, ISO 9705 room, BFD curve*

Introduction

The ability to predict temperatures developed in compartment fires is of great significance to the fire protection professional [1]. There are many uses for knowledge of compartment fire temperatures, including the prediction of: (1) onset of hazardous conditions, (2) property and structural damage, (3) changes in burning rate, (4) ignition of objects, and (5) the onset of flashover. Many methods have been developed to predict or model the compartment temperature during fire. Barnett [2] developed a single log-normal equation (BFD curve) as a new empirical model for fire compartment temperatures. He proposed a simple model of the temperature-time fire development in which only three factors are required: maximum gas temperature, the time at which this maximum temperature occurs, and a shape constant for the curve. Based on a large amount of data correlation [3] using BFD curves he recommended this simple equation can be used to replace international temperature-time curves such as ISO 834, BS 476, ASTM 119, NFPA 251, the external, the hydrocarbon, and the Eurocode parametric curve. Five main advantages of his method compared to other schemes were put forwards in his paper [2]:

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- the BFD curve is a "natural" fire curve that fits the results of actual fire tests closer than previously known fire modeling methods,
- the shape of the curve bears a strong relationship to both the pyrolysis coefficient and the opening factor,
- the shape of the curve is related to the thermal properties of the fire cell,
- contrary to a number of other fire modeling curves, the BFD curve does not need the use of a time shift, and
- it uses a single equation to model the temperature of both the growth and decay phases of a fire in a building whereas a curve such as the Eurocode 1 curve requires two equations.

The research presented in this communication focuses on using the BFD curve to fit the test results of 12 room scale tests in an ISO 9705 compartment. For the two-zone model of the compartment temperature distribution in room fires without flashover, the BFD curve is used to fit the temperature at different spatial points. The errors of the fitted curves are evaluated, with the aim that the test data and the model results may be used amongst the fire safety research community.

Experimental setup and facilities

Twelve wood crib fire tests were conducted inside an ISO 9705 room, in CSIRO's Fire Test Laboratory. The hood, exhaust duct, size of room and all instrumentation met the specifications of ISO 9705 [4]. The dimensions of the room are 3.6 m long, 2.4 m wide, and 24 m height. There is a single doorway opening to the outside centered on the south wall, as shown in fig. 1, with a width of 0.8 m and height of 2.0 m. The doorway was opened during all room tests. All room tests were conducted with only natural convection driving air ingress into the room. The open factor F_{O2} is 0.05087 m$^{0.5}$ as calculated by eq. 1:

$$F_{O_2} \quad \frac{A_v h_v^{0.5}}{A_T} \tag{1}$$

The exhaust gas from the room is collected by a hood outside the doorway. The gas analysis of the exhaust in the duct enabled the heat release from the burning crib to be determined by means of oxygen consumption calorimetry. The instrumentation in the duct met the specifications of ISO 9705. The sampling rate of ISO 9705 is 1 sample per 2.5 seconds.

Three thermocouple trees were used for each test, which were labeled as TC-North, TC-South, and TC-Doorway (fig. 1). Type K MIMS thermocouples (stainless steel sheathed, 1.5 mm diameter) were used on each tree. All trees were composed of 10 thermocouples which were spaced vertically at 200 mm increments, with the lowest thermocouple placed 300 mm from the floor (the uppermost thermocouple being 2100 mm from the floor or 300 mm from the ceiling). The tips of the thermocouples for the tree TC-North was located 100 mm from the north wall and 150 mm from the east wall. These thermocouples have been denoted Tnorth300, Tnorth500, *etc*. in this manuscript. Thermocouple tree TC-South was located in the south corner of the room with the tip of each thermocouple 100 mm from the south wall and 150 mm from the east wall; the thermocouples are denoted as Tsouth300 to Tsouth2100. All the thermocouples were connected to a data logger.

The nominal heat release rate (HRR) of these cribs was 0.15 MW, 0.25 MW, 0.5 MW, and 1.0 MW. Cribs were put in two positions inside the ISO room, at the center or at the corner. Eight tests were done on cribs placed at the corner with nominal HRR 0.15 MW, 0.25 MW, 0.5 MW, and 1.0 MW, while 4 tests were conducted on cribs at the centre of the room with the same four nominal HRR.

The wood cribs were made from two sizes of radiata pine wood sticks; dimensions of the sticks were either 35 mm × 35 mm × 500 mm (width × height × length) or 35 mm × 35 mm × 1000 mm. The cribs constructed for 0.15 MW, 0.25 MW, and 0.5 MW HRR only consisted of the shorter sticks. The 0.15 MW, 0.25 MW, and 0.5 MW cribs were composed of 2, 6, and 8 layers of sticks, respectively, with 8 sticks per layer. The 1 MW crib had 12 layers, 6 of which had 16 short sticks per layer and the other 6 layers had 8 long sticks per layer. Sticks had been conditioned at 23 ± 2 °C and 50% ± 5% relative humidity for more than one month before being tested. All the cribs were ignited by spirits in aluminum trays placed underneath the crib. The room environment, nominal fire size, initial mass and positions of these cribs are listed in tab. 1.

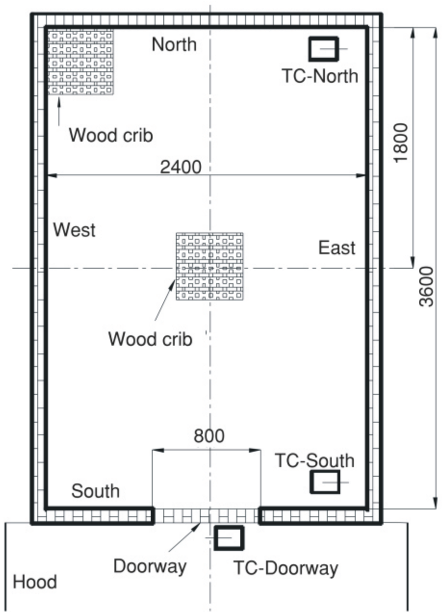

Figure 1. Test arrangement inside ISO 9705 room

Table 1. Cribs and room condition

Test label	Position	Nominal fire size [MW]	Initial mass [kg]	Room temp [°C]	Room humidity [%]
Test1	Corner	0.150	7.06	19.2	43.5
Test2	Corner	0.150	7.30	18.2	53.7
Test3	Corner	0.25	14.06	25.1	55.3
Test4	Corner	0.25	14.45	23.8	60.3
Test5	Corner	0.50	30.37	21.3	45.2
Test6	Corner	0.50	30.15	26.2	41.5
Test7	Corner	1.0	57.02	19.9	51.3
Test8	Corner	1.0	58.16	22.3	46.5
Test9	Center	0.150	7.12	18.6	53.2
Test10	Center	0.250	14.1	18.4	46.6
Test11	Center	0.50	29.5	17.4	47.3
Test12	Center	1.00	54.9	17.2	46.1

Results and discussion

Test results

Figure 2. shows the HRR curves for corner fires Test1 to Test8. Test1 and Test2 coincide well to each other, and have HRR peak over the nominal 0.15 MW, nearly 0.2 MW. The HRR peaks of both tests occur earlier than for the larger fires, at nearly 290 second from ignition time. This was attributed to the relatively large porosity factors [5] of these smaller cribs. The transport of air to the centre of these cribs is more rapid, resulting in quick flame spread through the crib. It appears that surface char formation does not impede the wood pyrolysis and significantly restrain combustion. Thus, the HRR curves are not significantly influenced by the char formation and decrease when the volatile component of the fuel is consumed.

For larger cribs, the HRR peaks occur at a later time. This is due to the more compact structure of the cribs. The burning is more significantly influenced by the effect of surface char formation as the porosity factor decreases. The HRR peak of Test3 and Test4 appears around 720 seconds from ignition time, while Test5 has its peak at 770 seconds and Test6 at 810 seconds. The peaks HRR of Test7 and Test8 are later than 900 seconds. Sharp peaks appear on the curves of Test5 and Test7, and this is due to the ignition of paper covering the gypsum panels that lined the room.

Figure 3 illustrates the HRR curves of the centre crib fires Test9 to Test12. As with the corner fires, the delay in reaching the peak HRR with crib size is apparent. Although the HRR reaches 1 MW in Test8, the lower layer temperature is still less than 500 °C. No flashover happened in the 12 tests.

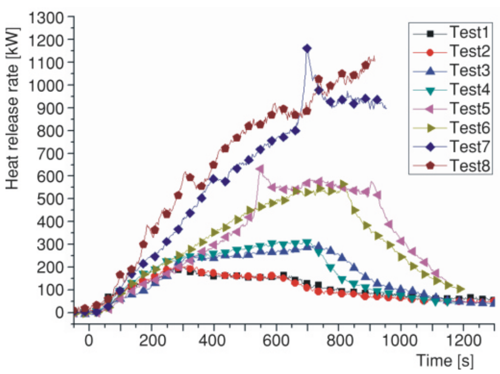

Figure 2. Corner fire HRR

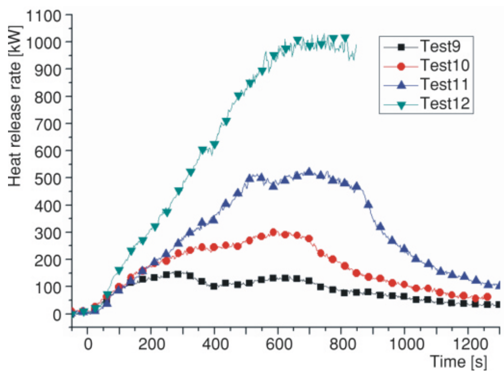

Figure 3.Center fire HRR

Ambient temperatures were subtracted from the measured temperatures. Figures 4 and 5 show the results of TC-North and TC-South in Test2, respectively.

The curves present are typical of what may be expected for a two-zone model of a compartment fire. The interface layer is near Tnorth1300 and Tsouth1300 which is 1300 mm above the floor. The Tnorth1300 and Tsouth1300 fluctuate severely as the flow of cooler incoming air shears against the flow of hotter, out-flowing exhaust gases promoting turbulence between the upper and lower zones. The temperature of the upper zone is significantly higher than

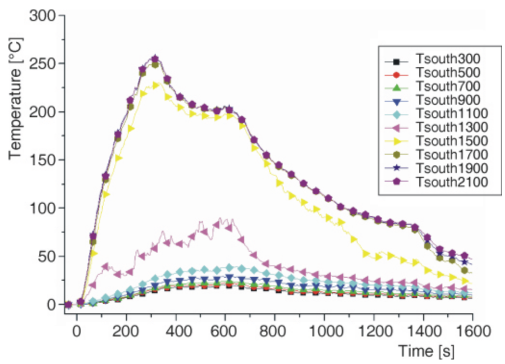

Figure 4. Compartment temperature of TC-South in Test2

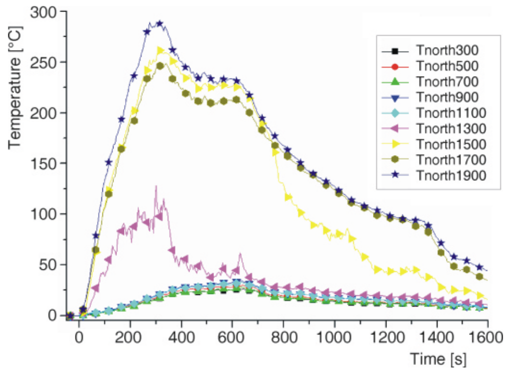

Figure 5. Compartment temperature of TC-North in Test2

that in the lower zone. The shape of the temperature curves in the upper zone mimics that of the HRR curve, not surprisingly as the upper zone temperature is dependent on HRR.

Modeling of temperature-time curve using the BFD equation

The basic equation that produces a "BFD Curve" is as follows [2]:

$$T = T_a + T_m e^{-z} \tag{2}$$

where T is the temperature at any time t, T_a – the ambient temperature, T_m is the maximum temperature generated above T_a, and

$$z = \frac{(\ln t - \ln t_m)^2}{S_c} \tag{3}$$

where ln is the natural logarithm (dimensionless numbers), t is the time from ignition of fire (Barnett uses minutes, we use seconds in this paper), t_m – the time at which T_m occurs, and S_c – the shape constant for the temperature-time curve (dimensionless numbers). Note that the ambient temperature is subtracted from all the compartment temperatures listed in tab. 1, therefore eq. 4 is substituted for eq. 2. The values of the parameters T_m and t_m for thermocouple tree TC-South and TC-North for all 12 tests are listed in tabs. 2 and 3.

$$T = T_m e^{-z} \tag{4}$$

The fitting error e_f is defined as:

$$e_f = \sqrt{\frac{1}{n(n-1)} \sum_{k=1}^{n} (T_d(k) - \bar{T}_d)^2} \tag{5}$$

where n is the total number of samples, and T_d – the difference between the test temperature T and the fitted value T_f, with

$$\bar{T}_d = \frac{1}{n} \sum_{k=1}^{n} T_d(k) \tag{6}$$

Table 2. T_m and t_m of TC-south

	Tsouth300		Tsouth500		Tsouth700		Tsouth900		Tsouth1100	
	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]
Test1	17.9	575	17.1	590	19.4	615	20.9	640	28.5	635
Test2	20.5	590	22.2	600	24.4	625	29.4	630	39.3	635
Test3	39.8	805	37.5	810	47.6	800	54.6	800	64.1	775
Test4	49.1	745	47.3	730	55.7	735	63.2	755	73.1	745
Test5	117.8	895	115.7	890	142.6	900	155.6	910	202.9	910
Test6	129.5	795	131.4	765	164.2	810	170.6	810	213.7	810
Test7	322.9	1045	314.9	1045	367.4	1045	411.9	1045	509.1	1045
Test8	133.9	665	135.6	665	178.6	665	224.3	665	261.8	660
Test9	19.1	620	22.1	630	26.9	630	33.7	655	104.3	595
Test10	49.3	720	57.2	705	66.7	700	78.5	705	110.5	700
Test11	108.8	890	122.3	880	147.6	890	249.5	895	351.3	890
Test12	298.1	840	322.9	840	368.2	840	409.1	840	499.3	840
	Tsouth1300		Tsouth1500		Tsouth1700		Tsouth1900		Tsouth2100	
	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]
Test1	81.9	445	199.2	320	231.9	300	239.8	295	235.6	295
Test2	89.7	580	230.5	335	251.1	330	256.1	320	255.3	330
Test3	78.2	800	304.7	770	334.2	735	339.4	730	338.3	730
Test4	87.7	740	323.4	700	362.7	640	366.2	640	363.9	685
Test5	347.7	910	487.4	900	519.8	850	530.6	850	531.1	850
Test6	313.5	805	497.7	805	541.6	755	546.3	735	539.5	765
Test7	648.4	1040	690.9	1040	705.1	1035	713.1	1035	713.1	1035
Test8	500.9	640	567.6	640	588.1	640	607.5	665	597.6	665
Test9	175.4	315	188.9	305	190.5	305	191.2	290	192.1	295
Test10	288.1	670	317.6	635	328.7	620	333.8	620	330.2	620
Test11	410.5	710	508.3	785	531.3	795	548.5	715	550.7	730
Test12	739.6	840	788.9	840	814.4	840	824.7	840	821.6	840

Table 3. T_m and t_m of TC-North

	Tnorth300		Tnorth500		Tnorth700		Tnorth900		Tnorth1100	
	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]
Test1	24.1	615	28.5	610	19.5	585	29.6	580	22.7	610
Test2	26.4	650	30.2	645	28.1	635	34.4	635	32.9	640
Test3	58.3	755	–	–	–	–	–	–	61.7	810
Test4	64.7	710	75.1	690	63.7	710	80.7	720	70.1	720
Test5	142.9	900	166.4	905	146.6	905	171.4	910	161.8	905
Test6	163.7	805	187.2	800	169.9	805	196.9	805	179.9	805
Test7	357.1	1040	402.5	1045	369.8	1045	411.1	1045	451.8	1050
Test8	163.6	660	201.5	650	236.6	650	236.2	650	226.1	650
Test9	14.8	670	16.6	670	18.3	660	23.1	660	107.5	555
Test10	40.9	695	45.3	700	45.1	690	56.4	690	66.5	700
Test11	94.1	885	110.9	890	119.4	885	142.3	885	278.2	895
Test12	299.3	880	360.4	880	384.1	880	533.1	880	610.3	880
	Tnorth1300		Tnorth1500		Tnorth1700		Tnorth1900		Tnorth2100	
	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]	T_m [°C]	t_m [s]
Test1	117.2	265	184.5	300	216.4	295	254.7	290	–	–
Test2	128.1	305	261.2	315	249.2	345	289.2	280	266.7	280
Test3	73.5	755	356.4	725	361.7	750	416.1	725	453.8	740
Test4	82.4	705	342.8	600	428.2	685	464.1	690	504.2	675
Test5	283.7	970	569.5	910	672.3	865	731.8	805	807.6	820
Test6	277.3	925	598.2	810	683.6	785	745.5	780	808.6	755
Test7	687.3	1050	899.1	1040	935.5	1035	956.2	1035	966.1	1045
Test8	545.8	630	689.4	640	732.6	625	779.2	565	–	–
Test9	167.7	310	174.2	305	176.6	305	176.6	305	123.4	305
Test10	280.2	645	294.6	645	297.2	645	297.7	645	227.4	640
Test11	361.8	885	446.2	740	466.4	745	477.2	740	389.2	740
Test12	687.3	840	708.9	840	727.9	800	743.1	800	647	800

According to Barnett's study [2], S_c is calculated based on following equations:

– for uninsulated fire compartments

$$S_c \quad \frac{1}{4.00F_{O2} \quad 0.10} \tag{7}$$

– for insulated fire compartments

$$S_c \quad \frac{1}{9.25F_{O2} \quad 0.21} \tag{8}$$

For the ISO 9705 room, S_c is 3.30 for an uninsulated room and 1.47 for an insulated room. But these values are not appropriate to all tests. The typical value of S_c calculated by recommended equations does not fit the data very well, but the fit can be improved by varying this constant.

Equation 4 is used to fit the compartment temperatures. Figure 6 is the model result for two temperature curves in the upper zone, while fig.7 shows the two results for the lower zone,

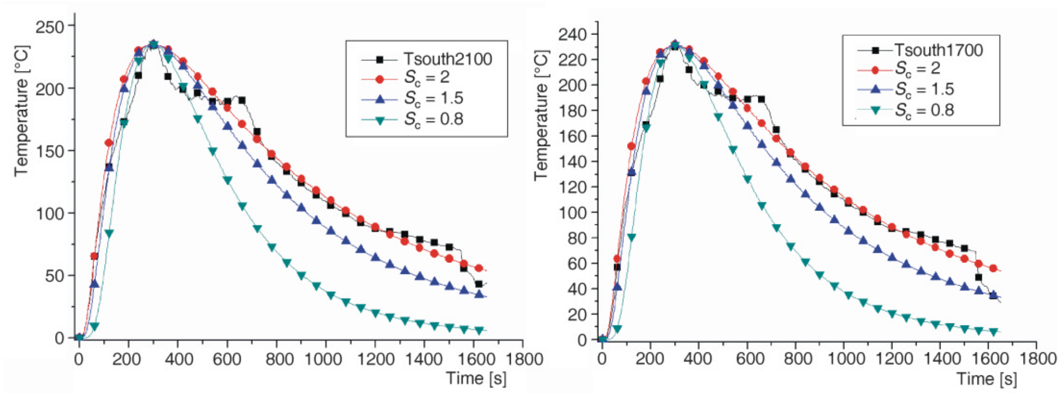

Figure 6. Fitting of upper zone temperature

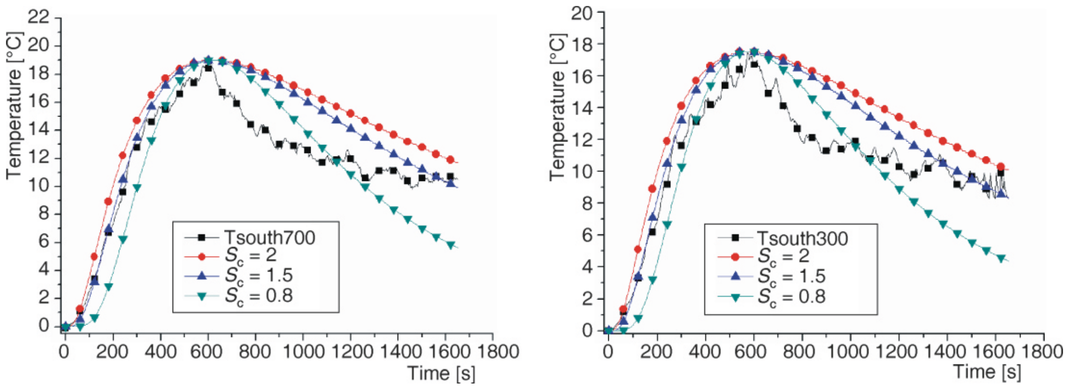

Figure 7. Fitting of lower zone temperature

all for the TC-South thermocouple tree. It can be seen that the value of S_c that gives the better fit to the experimental data differs depending on whether the thermocouple is placed in the hotter upper zone or the cooler lower zone. The model curve with $S_c = 2$ gives the best fit to the measured temperature for the upper zone. The agreement between model data and experimental data is much closer for temperatures in the upper zone than for those in lower zone. This was also true for the results are obtained for TC-North.

The fitting error (e_f) is calculated for different shape constant (S_c). A typical result is shown in fig. 8. The value of e_f varies from 0.04 to 0.06 for S_c values of 1.5 to 3 for upper zone curves (Tsouth1500 to Tsouth2100). This implies the fact that the values of S_c that give the best fit lie between the values calculated for insulated and uninsulated rooms. The large fluctuations in the temperature measured at Tsouth1300, which is placed near the interface between the upper and lower zones, results in a large value of e_f regardless of the value of S_c. For the lower zone, the range of S_c that provides the best fit is from 1.8 to 3.2 with e_f from 0.07 to 0.09.

Figure 9 illustrates the minimum fitting error with corresponding shape constant for TC-South fittings in all tests. Test1, Test8, and Test12 have the lowest fitting errors, while Test5, Test7, and Test11 have the largest errors. The error depends on the original shape of temperature curves. Test5 and Test7 have abnormal peaks caused by burning of cover paper.

Figure 11 illustrates the minimum fitting error with corresponding shape constant for TC-North fittings in all tests. Test1, Test8, and Test12 have the

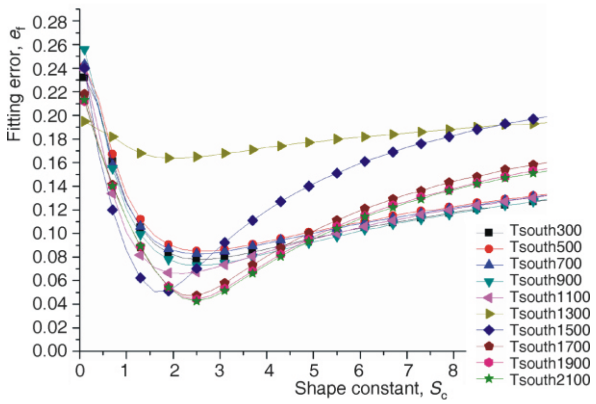

Figure 8. Fitting errors with different S_c

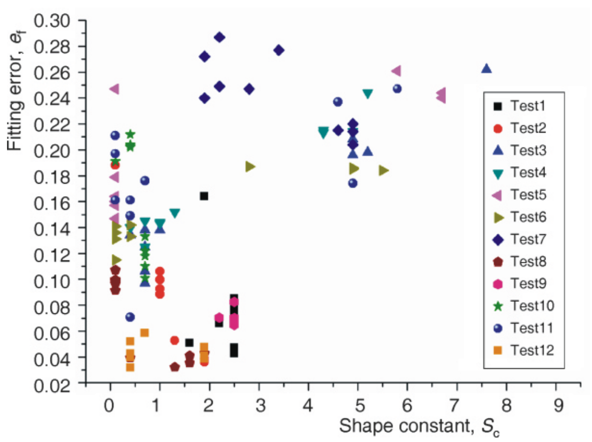

Figure 9. The minimum fitting error with the thermocouple position for TC-South in all test

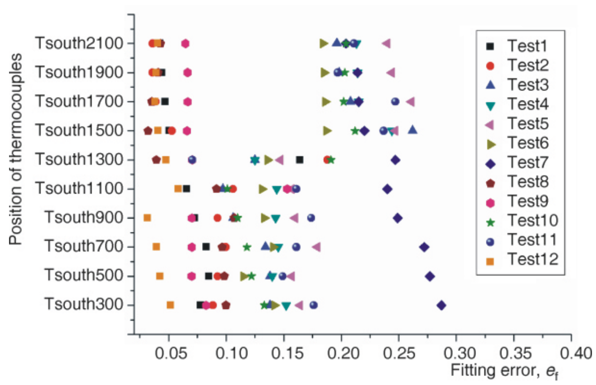

Figure 10. The minimum fitting error of fitting for TC-South

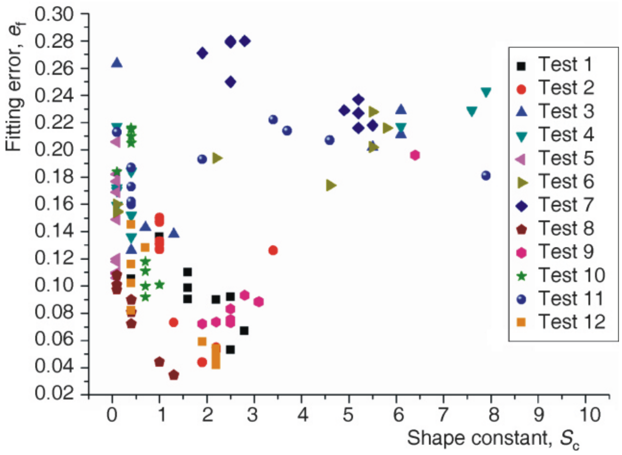

Figure 11. The relationship of minimum fitting error and S_c in fitting of TC-North

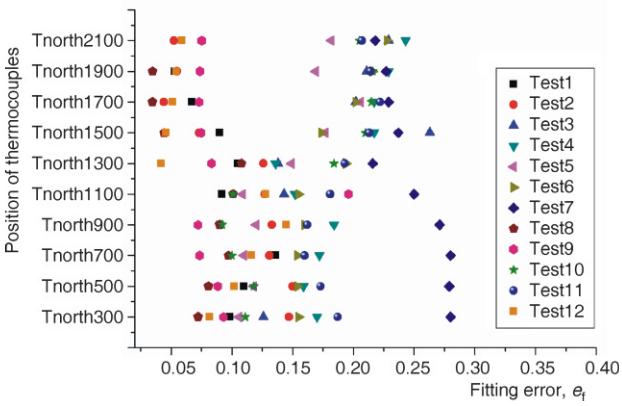

Figure 12. The minimum fitting error of fitting for TC-North

lowest fitting errors (which is same as those in TC-South – refer fig. 9), while Test7 and Test11 have the largest errors.

Figure 12 illustrates the minimum fitting errors for TC-North in all tests. It shows similar results as given in fig. 10. The overall error in the lower zone is less than that in upper zone, and the errors are grouped between 0.05 and 0.20, except for Test7. The 1300 mm level is an interface level for both TC-South and TC-North. Above this level the error is separated into two groups with fitting error from 0.03 to 0.07 (Test1, Test2, Test8, Test9, and Test12) and from 0.17 to 0.27 (Test3, Test4, Test5, Test6, Test7, Test10, and Test11). This does not appear to be any relationship between the position of the cribs or fire size as to what grouping the data is placed.

Conclusion

The temperature-time data for a crib fire in an ISO 9705 size room were modeled using a BFD curve. A good fit between experimental and model data could only be obtained when the constant S_c could be varied, *i. e.* it could not be predicted accurately from the equation given in the model. The shape of the predicted curve seemed to fit the temperature in the upper zone of the room more accurately than in the lower zone of the room. Clearly, more research is needed for the temperature distribution in the room to be predicted with such simple models. Sharing the fire test data-base resource in the fire safety research community would be helpful towards meeting this goal.

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Nomenclature

A_F – floor area of the compartment, [m^2]
A_T – internal surface area less opening, [m^2]
A_v – sum of areas of vertical openings, [m^2]
e_f – fitting error based on dimensionless temperature T_d/T_m, [–]
F_{O_2} – opening factor based on $A_F = A_v h_v^{0.5}$, [$m^{0.5}$]
F_v – ventilation factor of vertical openings ($= A_v h_v^{0.5}$), [$m^{2.5}$]
h_v – weighted mean height of vertical openings, [m]
Q – energy output from fire, [kW]
S_c – shape constant for the temperature-time curve, [–]
T – temperature at any time, [°C]
T_a – ambient temperature, [°C]
T_d – difference between test temperature and fitting value ($= T - T_f$), [°C]
T_f – fitting temperature at any time, [°C]
T_m – maximum temperature generated above T_a, [°C]
t – time from ignition of fire, [s]
t_m – time at which T_m occurs, [s]

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