TOTAL HEAT FLUX ON THE WALL: BENCH SCALE WOOD CRIB FIRES TESTS

by

Qiang XU^a, Xinggui QUE^b, Liying CAO^b, Yong JIANG^{c*}, and Cong JIN^a

^a School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China

^b Shanghai Fire Research Institute of Public Security Ministry of China, Shanghai, China ^c State Key Laboratory of Fire Science, University of Science and Technology of China,

Hefei, China

Original scientific paper UDC: 662.63:536.24 DOI: 10.2298/TSCI1001283X

A serials test of crib fire conducted in a bench scale compartment. Total heat flux to the wall is measured by Schmidt-bolter gages in upper zone and lower zone of the compartment. The heat flux intensity and distribution of these quasi-steady crib fires is evaluated through these tests. The peak value and integral of the measured total heat flux is scaled with exposed surface area of wood cribs. Linear relations of these scaled value with the mass and exposure surface area of wood cribs are obtained. The ratio of scale value in upper and lower zone is also presented which could be used as model in estimating thermal load to side wall for bench scale tests.

Key words: wood crib fire, heat flux, compartment test, zone model

Introduction

The performances of fire are important in dealing with problems related to fire detection, fire heating of building structures, and human and properties protection. Much works has been done to explore gas temperatures and burning rates in compartment fires. But less research has been carried out to study one important fire performance, which is the thermal load generated by fire towards wall. As it is an important concern for construction design, the building codes or fire codes specified statutory requirements pertaining to the heat flux to wall for fire safety design [1].

Some researches focused on prediction of the radiative heat flux from a flame to determine ignition and fire spread hazard, and in the development of fire detection devices. But the shape of flames under actual conditions is arbitrary and time dependant, which makes detailed radiation analysis very cumbersome and uneconomical [1]. Furthermore convection plays an important role in heat transfer during a compartment fire. It transfers the enormous amount of chemical energy released during a fire to the surrounding environment by the motion of hot

^{*} Corresponding author; e-mail: j0805481@public1.ptt.js.cn

gases. In case of compartment fire, hot gases from fire plume rise directly above the burning fuel and impinge on the ceiling which results in ceiling jet. The ceiling jet move horizontally under ceiling to other areas until meets the side wall. While the hot gases layer grows thicker, part of the jet flow moves downwards along the side wall. Thus, the heat flux through the side wall is made up of radiation from flame and convection of thermal flow inside compartment. Fire endurance of wall material should be evaluated by certain heat flux load under an assumed fire exposure. Total heat flux measurement is necessary and more meaningful in compartment fire research. Lattimer used different size of square and line propane burners with heat release rates ranging from 25 to 300 kW to study total incident heat flux onto the non-combustible [2] and combustible [3] corner. Empirical relations for estimating the incident heat fluxes were developed from these tests. Ohlemiller [4] used two square propane gas burners as fire initiation source in ISO 9705 room with a corner covered by lining material. The heat flux distribution in the corner area was measured by Schmidt-Boelter total flux gages. Contours of constant heat flux on corner wall were given for the two scales burner. Tofilo [5] used square pan fires of industrial methylated spirits as fire source to study heat flux on side walls. Croce [6] used wood crib fires in enclosures to study heat load on side wall during quasi-steady stage. The relationship of scaled radiation and ventilation parameters were given by their research. The study addressed in this paper was conducted in bench scale with quasi-steady wood crib fire. The measured total heat flux is give by its relationship with the mass and geometric shape of wood crib. The characteristics of total heat flux to the side wall in upper and lower zone of the compartment are illustrated.

Experiment setup and facilities

Wood crib fire is closer to the real compartment fire than pool or spray fire. Fire behavior of wood crib is important in room fire research when it is used as fire source, thus wood cribs made of white pine are used in these tests. The definition of wood cribs is given in the SFPE Handbook of Fire Protection Engineering [1], which is defined as the wood structure with regular, three dimensional array of wood sticks. Each stick is of a square cross-section and of a length much greater than its thickness. The sticks are placed in alternating rows, with an air space separating horizontally adjacent sticks. Two regimes, which are surface area-controlled burning and porosity-controlled burning, were discovered by Gross [7] based on mass loss rate for wood cribs burning in open space. Porosity factor [7] was defined for crib research, and it can be calculated from following equations. For a wood crib, *l* is the length of stick, *b* – the cross-section of the stick, *N* – the layer of crib, and *n* – the number of stick per layer, the porosity factor ϕ is:

$$\phi \quad \sqrt{N}b^{1.1}\frac{A_{\rm v}}{A_{\rm s}} \tag{1}$$

where A_s is the exposed surface area of the wood crib,

$$A_{s} nN(4lb \ 2b^{2}) (N \ 1)n^{2}b^{2}$$
 (2)

and $A_{\rm v}$ is the opening area at the base of the wood crib,

$$A_{\rm v} = (l - nb)^2 \tag{3}$$

Table 1 illustrates the parameters of wood cribs where s is the space between stick, h - the height of crib, and R – the mass loss rate. The cross-section size of each stick is 10×10 mm.

Crib label	<i>l</i> [cm]	N	s [cm]	<i>h</i> [cm]	$A_{\rm v}$ [cm ²]	$A_{\rm s}$ [cm ²]	п	φ [cm ^{1.1}]	R [%]	Initial mass/g
10-5		5		5		950		0.0588	0.428	112
10-10	10	10	1.25	10	25	1875	5	0.0422	0.307	224
10-12	10	12	1.23	12	25	2245		0.0386	0.281	269
10-15		15		15		2800		0.0346	0.252	336
12-5		5		5		1356		0.0594	0.432	156
12-10	12	10	1.2	10	36	2676	6	0.0425	0.309	307
12-12	12	12	1.2	12	50	3204		0.0389	0.283	394
12-15		15		15		3996		0.0349	0.254	497
15-5	15	5		5		2224		0.0493	0.359	266
15-10		10	10	10	40	4384	0	0.0353	0.257	564
15-12	15	12	1.0	12	47	5248	0	0.0323	0.235	664
15-15		15		15		6544		0.0290	0.211	791

 Table 1. Parameters of wood crib

Wood sticks had been conditioned more than one month before burning test. The conditioning room is with 23 2% in temperature and 50 5% in humidity. The average density of crib is 439 kg/m³. All the cribs were ignited by 25 milliliters of heptane in a steel plate (160 millimeters in diameter) underneath the crib.

The size of compartment is 1400 1000 200 mm (length width hight) with a 100 1200 mm (width hight) opening.

Two Schmidt-bolter total flux gages are mounted on the side wall with their surface flushed with internal wall. The distance from gage surface to axis of crib flame is 500 mm. One is 300 mm above the floor, which is labeled as low-gage, and the other is 900 mm above the floor, which is labeled as up-gage.

A thermocouple tree is placed at the corner of compartment. 10 Type K thermocouples are on the tree with naked wires 0.2 mm in diameter. They are labeled as T110 to T1100 with 100 mm increments from 110 mm to 1100 mm (which is 100 mm below the ceiling) above the floor. All the thermocouples were connected to a data acquisition system with a sampling rate 1 sample per second.

Results and discussion

Selected time history curves of total heat flux of up-gage and low-gage are illustrated in figs. 1 and 2, respectively. Overall up-gage amplitude is more than that of low-gage along the



combustion procedure. The tendency of each curve reproduces the shape of heat release rate, and all have double-peaks. Although the porosity factors of these cribs belong to the range leading to single heat release rate (HRR) peak [8], no single peak HRR appears. That would be caused by the size of stick is larger than that mentioned in [8]. Flame can not spread all over the crib quickly. This relatively slow propagation causes the char formation effect overtakes the pyrolysis effect. The overall burning is restrained by char formation, thus the HRR decreases to form a middle trough. This implies that porosity factor is not the only governing factor in controlling the burning model of wood crib fire. A second peak corresponds to the post-surface char formation stage while an increased rate of volatiles formation was achieved. The second peak



Figure 3. Compartment temperature in test 10-15 (color image see on our web site)

caused by the total burning of crib is much higher than the first one (except in test 12-5, in which the relatively looser structure causes quick burning of crib). The radiation intensity from flame and convection magnitude inside the compartment depends on the HRR strongly. This results in the shape of total heat flux to the side wall reflects the change of HRR.

Figure 3 shows the compartment temperature in test 10-15. The curves present a typical two-zone model of this compartment fire. The interface layer is near T660 which is 660 mm above the floor. The T660 fluctuates severely as a turbulent flow appears between control volume of upper and lower zone. The temperature of the upper zone is greater than that in lower

zone. This confirms that the low-gage (300 mm above floor) and up-gage (900 mm above floor) are in lower zone and upper zone, respectively.

More attention is paid on the heat flux peak and the total thermal load of heat flux to the wall during burning procedure. The peaks (labeled as q_{peak} , with unit in kW/m²) and integral of heat flux (labeled as q_{wall} , with unit in MJ/m²) during burning stage for all tests are illustrated in figs. 4 and 5, respectively. The position of up-gage is in upper zone of compartment during



Figure 4. Peak of heat flux of all tests (q_{peak})



fire process. The heat flux to the side wall consists of radiation from fire plume and smoke, and convection of hot gases. The value of up-gage is quite greater than that of low-gage which is in lower zone with radiation from the root of plume and very weak convection.

Peak of total heat flux and the integral of heat flux are treated with wood crib exposed surface area A_s . The results are illustrated in figs. 6 to 9 vs. A_s and initial mass.

In figs. 6 and 7 q_{peak} is multiplied by exposed area A_s (which unit is in m²), then is drawn against mass and A_s , respectively. Linearly fitted result is also drawn with the test curves. The $q_{\text{peak}} \cdot A_s$ (with unit in kW) increases linearly along with the initial mass and A_s . The up-gage line has greater ratio of slop than that of low-gage. Table 2 lists the fitting uncertainty of fittings in figs. 6 and 7.



Figure 6. q_{peak}: A_s vs. A_s

Figure 7. $q_{\text{peak}} \cdot A_s$ vs. mass

Table 2.	Uncertainty	of fitting	result in	figs. 6 and 7

	Up (fig. 6)	Low (fig. 6)	Up (fig. 7)	Low (fig. 7)
Confidence [%]	99.16	98.40	99.19	98.43
Standard deviation [kW]	0.0673	0.0323	0.0660	0.0320

In figs. 8 and 9 q_{wall} is multiplied by exposed area A_s (which unit is in m²), then is drawn against mass and A_s respectively. Linearly fitted result is also drawn with the test curves. The $q_{wall} A_s$ (with unit in MJ) increases linearly along with the initial mass and A_s . The same as shown in figs. 6 and 7, the up-gage's line has greater ratio of slop than that of low-gage. Table 3 lists the fitting uncertainty of fittings in figs. 8 and 9.



Figure 8. q_{wall}·A_s vs. A_s

Figure 9. qwall As vs. mass

Table 3.	Uncertainty	of fitting	result in	figs. 8 and 9
	•			0

	Up (fig. 6)	Low (fig. 6)	Up (fig. 7)	Low (fig. 7)
Confidence [%]	95.14	94.45	96.35	95.71
Standard deviation [MJ]	0.481	0.199	0.418	0.176

Figures 10 to 13 illustrate the ratio of the values from up-gage and low-gage. It shows the tendency of each ratio tends to be constant as initial mass or exposed surface area increases. This would be helpful in predict heat flux from other similar larger fire source.

3.0



Figure 10. Ratio of up- and low-gage maximum heat flux (q_{peak}) vs. A_s

Figure 11. Ratio of up- and low-gage maximum heat flux (q_{peak}) vs. mass





Figure 12. Ratio of up- and low-gage overall heat flux (q_{wall}) vs. A_s

Figure 13. Ratio of up- and low-gage overall heat flux (q_{wall}) vs. mass

Conclusions

This research would be helpful in working as a basis for establishing heat flux prediction model which is used to estimate external fire size tolerance of lining material for construction usage. With these scaled results and considering geometric parameters of compartment, it would be expected to achieve an overall heat flux model to side wall for an enclosure fire and then verify it. Tracing the heat source is also important in analysis total heat flux. This would help to weight the heat amount from radiation and convection. The result can be used as reference to adopt suitable protection measures to prevent radiation and convection.

Acknowledgments

The research is supported by the Natural Science Fund of China, No. 50876045. This research also used the facilities established from Natural Science Fund of Jiangsu Province, No. BK2008416 and financial support from State Key Laboratory of Fire Science, No. HZ2007-KF11.

References

- [1] ***, The SFPE Handbook of Fire Protection Engineering, 3rd ed., ISBN: 087765-451-4, pp. 3-13-15
- [2] Lattimer, B. Y., Sorathia, U., Thermal Characteristics of Fires in a Noncombustible Corner, *Fire Safety Journal*, 38 (2003), 8, pp. 709-745
- [3] Lattimer, B. Y., Sorathia, U., Thermal Characteristics of Fires in a Combustible Corner, *Fire Safety Journal*, 38 (2003), 8, pp. 747-770
- [4] Ohlemiller, T., Cleary, T., Shields, J., Effect of Ignition Condition on upward Flame Spread on a Composite Material in a Corner Configuration, *Fire Safety Journal*, 31 (1998), 4, pp. 331-344
- [5] Tofilo, P., et al., Wall Heat Fluxes in Enclosure Fires, Proceedings, 6th Asia-Oceania Symposium on Fire Science and Technology, 2004, Daegu, Korea, pp. 108-119
- [6] Croce, P. A., Yin, Y., Scale Modeling of Quasi-Steady Wood Crib Fires in Enclosures, *Fire Safety Journal* 40 (2005), 3, pp. 245-266
- [7] Gross, D., Res, J., National Bureau of Standards, C, Engineering Instrumentation, 66C (1962), 99

[8] Xu, Q., Study of Burning Behavior of Small Scale Wood Crib with Cone Calorimeter, Journal of Thermal Analysis and Calorimetry, 91 (2008) 3, pp. 787-90

Paper submitted: March 17, 2009 Paper revised: August 30, 2009 Paper accepted: August 30, 2009