Study on the Estimation of the Hazard to Evacuation Due to Wind-blown Fire Flow Induced by Urban Fire

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ABSTRACT

In the earthquake disaster management plans of most of the municipalities in Japan, the hazard to evacuation of city residents due to post-earthquake fires is estimated usually with regard to effect of radiation, but due attention is seldom paid for fire flow induced by city conflagration. Concerning the evacuation in urban fire, we should seriously pay attention to the hazard due to the fire flow that is blown over by a high wind and covers over a wide urban district. The tolerable exposure limits of human body to its elevated temperature and poisonous gases are very low. In addition the hazards caused by the hot smoke are considered to render considerable difficulty in fire fighting as well, so may affect the fire spread itself.

The final goals of this study are to analyze the causes of heavy toll of human lives that claimed by many urban fires in Japan in the past and to find effective measures to mitigate the hazard due to urban fire. For the first step, this paper aims at establishing a methodology to assess the hazard area due to fire flow in an urban conflagration in the past. More specifically, on the basis of an urban fire spread chart of Sakata City Fire, which broke out in 1976, wereconstruct the area of fire spread and estimate the temperature rise in the area due to the fire flow with the elapsed time after the onset of the fire.

KEY WORDS: fire flow, urban fire, estimation of hazard

1. INTRODUCTION

Urban fires have claimed tremendous number of human lives in Japan, where its cities have been congested with wooden houses. In both of the Kanto Great Earthquake in 1923 and the Great Tokyo Air Raid, approximately a hundred thousand of Tokyo residents were burnt to death by the fires that broke out almost simultaneously here and there in the city. For another example, as many as 2,165 people were killed by the fire that broke out in Hakodate, 1934, under a severe wind and accompanied by numerous firebrands.

Undeniably these fires were among the most ferocious ones in the history of the fires in the world. But still, a question has not yet solved: why so many people had to die while the velocity of urban fire spread is only several hundred meters per hour at most and the travel speed of people is ten times faster? Such a huge death toll may be partly attributed to the numerous fire which occurred simultaneously, but the city plans and the hot gas flows induced by the fires may have caused difficulty of the evacuation of the residents.

For rational and effective mitigation plan against post-earthquake fires, analyses should be made of the evacuation under the exposure to the fire flow. Having it in mind to reconstruct the evacuations in such severe urban fires in the past, this study addresses for the first step the reconstruction of the hazard due to the fire flow in Sakata City Fire, in which there was no death associated with the fire induced flow.

2. OUTLINE OF THE SAKATA CITY FIRE

The reason that Sakata City Fire is chosen in this study despite of no death toll in the fire is that the fire is a relatively recent urban fire in Japan so reasonably detailed information is available for the analyses from the fire investigation made at that time.

The outline of the fire is summarized in TABLE 1, and its fire spreading chart is as shown in Fig.1. The fire which broke out at 5:40 p.m., 29 October, 1976, were fanned by the strong wind with velocity about 10m/s in average and, despise of the rainy weather, burned down the 22.5ha of city area and 1,774 houses, which extended to Niida River, to ashes by 4 a.m., next morning.

TABLE 1: Outline of the Sakata City Fire

DATE OF THE FIRE	5:40p.m. 29 Octover 1976
ADRESS OF THE FIRE	Greenhouse 2-5-33 Nakamachi Skata City Yamagata
BURNT AREA	22.5ha
NUMBER OF BURNT HOUSES	1,774 houses
FLOOR AREA (WOODEN HOUSES)	130,845m^2(1673 houses)
FLOOR AREA (UN-WOODEN HOUSES)	21,281m^2(61 houses)

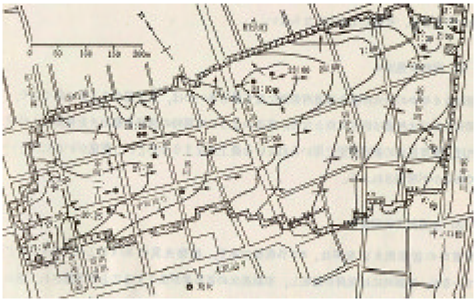


Fig. 1: Fire spreading chart of the Sakata City Fire

3. RECONSTRUCTION OF URBAN FIRE SPREAD

3.1 CALCULATION OF THE LOCATION OF FIRE SPREAD FRONT

From the fire spread chart which is generated based on the after event investigations of an urban fire, we can get the information on the courses of the fire spread, i.e. the direction of the fire spread, with time and the fire front lines at certain selected time after the onset of fire. Let i be the number identifying a course of fire spread, j be the number identifying a fire front at a given time, $\{x(i,j), y(i,j)\}$ be the location of the intersection of the course of fire spread i and the concurrent fire front j, and $t(i,j)$ be the time from the occurrence of fire, as shown in Fig.2. In other words, it follows that $\{x(i,j), y(i,j)\}$ denotes the location of the fire front in direction i at the selected time $t(i,j)$, for which the same time line is drawn in fire spread chart. The location of the fire front on the course of fire spread at arbitrary time t_f , which falls in $t(i,j) \le t_f < t(i,j+1)$ is calculated by interpolation. Assuming the fire spread velocity $\mathbf{v} = (v_x, v_y)$ be the same between the front line j and the adjacent line $j+1$, we have

$$v_x = \frac{x(i,j+1) - x(i,j)}{t(i,j+1) - t(i,j)} \quad \text{and} \quad v_y = \frac{y(i,j+1) - y(i,j)}{t(i,j+1) - t(i,j)} \tag{1}$$

The location of the fire spread front $P(i,t_f)$ on the course of fire spread i at an arbitrary time t_f, $\{x(i,t_f), y(i,t_f)\}$ is given as

$$x(i,t_f) = x(i,j) + v_x \times (t_f - t(i,j)) \quad \text{and} \quad y(i,t_f) = y(i,j) + v_y \times (t_f - t(i,j)) \tag{2}$$

By joining the two location which adjoin each other successively, the fire spread front line at an arbitrary time t_f can be generated as illustrated in Fig.2..

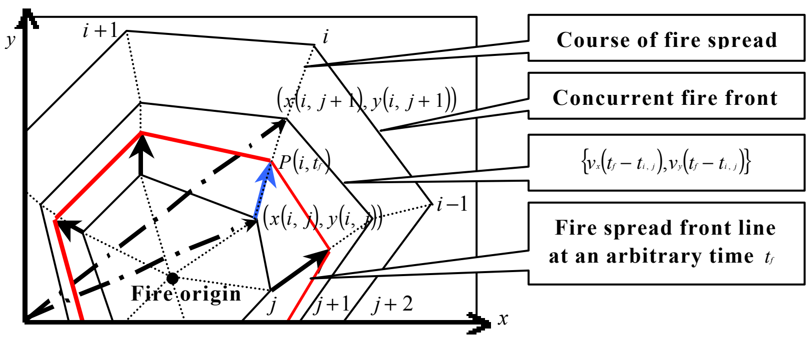


Fig.2: Fire spread front area

3.2 EXPRESSION OF MESH IN AN URBAN DISTRICT

An urban district is divided into multiple meshes by lines $x = x_m(k)$ $(k = 1, K)$ and $y = y_m(l)$ $(l = 1, L)$ as illustrated in Fig.3. in order to investigate the state regarding combustion and the temperature rise due to fire flow. The center of mesh (k,l), i.e. $\{gx(k), gy(l)\}$ is given as at an arbitrary point in an urban district

$$gx(k) = (x_m(k) + x_m(k+1))/2 \quad \text{and} \quad gy(l) = (y_m(l) + y_m(l+1))/2 \tag{3}$$

3.3 JUDGEMENT IF A MESH IS INVOLVED IN FIRE OR NOT

Clearly, the area that is enclosed by the fire front line at time t_f is the area that has been involved in the fire, and the area that is outside of the enclosing line is the area that is intact by the fire. Whether or not, a certain location of the city area is already involved in fire is judged by the following method.

The fronts of fire spread at an arbitrary time t_f form a polygon that consists of the segments linking the adjacent points of $P(i,t_f)$ $(i = 1, M)$. The equation of each segment $\overline{P(i,t_f)P(i+1,t_f)}$ is

$$\begin{Bmatrix} x \\ y \end{Bmatrix} = (1-d)\begin{Bmatrix} x(i,t_f) \\ y(i,t_f) \end{Bmatrix} + d\begin{Bmatrix} x(i+1,t_f) \\ y(i+1,t_f) \end{Bmatrix} \qquad (0 \le d \le 1) \tag{4}$$

The polygon is scanned by the coordinates of the center of meshes $x = gx(k), (k = 1, K)$, successively. If $x = gx(k)$ meets the following condition

$$x(i,t_f) \le gx(k) < x(i+1,t_f) \qquad \text{or} \qquad x(i+1,t_f) \le gx(k) < x(i,t_f) \tag{5}$$

the line $x = gx(k)$ and the segment $\overline{P(i,t_f)P(i+1,t_f)}$ intersect. In this case substituting $x = gx(k)$ into Eq.(4), the value of parameter d is obtained as

$$d = \frac{gx(k) - x(i,t_f)}{x(i+1,t_f) - x(i,t_f)} \tag{6}$$

Then, y coordinates of the intersecting point of the line $x = gx(k)$ and the segment $\overline{P(i,t_f)P(i+1,t_f)}$ is expressed in terms of parameter d

$$y = y(i,t_f) + d \times \{y(i+1,t_f) - y(i,t_f)\} \tag{7}$$

In the case of intersecting the line $x = gx(k)$ and the segment $\overline{P(i,t_f)P(i+1,t_f)}$ except when the line $x = gx(k)$ is tangent to the apexes of the polygon, the number of the intersecting points found by the above way is unexceptionally even number. When they are arranged in order from the lowest value of y, like $ykk(1), ykk(2), \cdots\cdots ykk(n)$, if $gy(l)$ is from an odd intersecting point to an even point, mesh (k,l) is inside of the polygon. The procedure of this judgment is illustrated in Fig.3..

CONDITION ($e = 1, n/2$)	**JUDGEMENT**
$gy(l) < ykk(1)$	OUT
$ykk(2e-1) \le gy(l) \le ykk(2e)$	IN
$ykk(2e) < gy(l) < ykk(2e+1)$	OUT
$ykk(n) < gy(l)$	IN

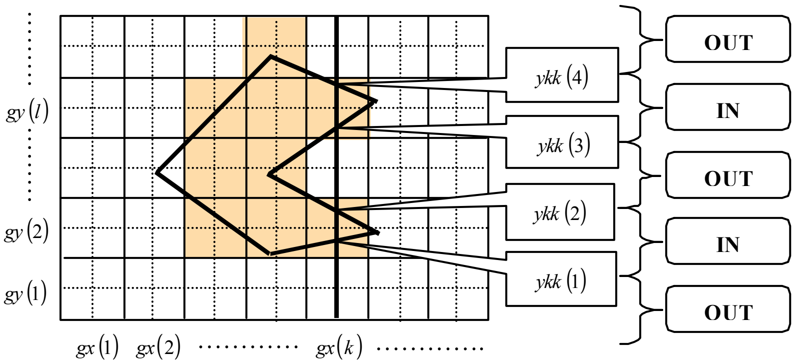


Fig.3: Judgment for searching the meshes in the polygon

3.4 COMPUTATION TO CLASSIFY MESHES BY THE STATE OF COMBUSTION

We classify the state of each mesh into three types: the state before burning, under burning and after burning. Letting $Tmesh(k,l)$ be the time since mesh (k,l) is first involved in the burning. According to the value of $Tmesh(k,l)$, the variable $Mflag(k,l)$ is given the number as follows to identify the state of burning of the mesh (k,l).

$$Mflag(k,l) = \begin{cases} 0 \ : \text{Before burning state} & (Tmesh(k,l) = 0) \\ 1 \ : \text{Under burning state} & (0 < Tmesh(k,l) < t_d) \\ 2 \ : \text{After burning state} & (t_d \le Tmesh(k,l)) \end{cases} \tag{8}$$

where t_d is the duration of the burning of a house and is calculated as follows:

Assuming the quantity of wood used in a steel-frame house and a wooden house be $85\,\mathrm{m}^3/\mathrm{m}^2$ and $180\,\mathrm{m}^3/\mathrm{m}^2$, respectively, the quantity of live combustibles be $30\,\mathrm{kg}/\mathrm{m}^2$ and the density of wood be $0.5\,\mathrm{kg}/\mathrm{m}^3$, the average quantity of combustibles per floor area is given as $180 \times 0.5 + 30 = 120\,\mathrm{kg}/\mathrm{m}^2$, where the quantity of wood used in a steel-frame house is ignored, for its value is much lower than the value of a wooden house. The burnt floor area of wooden houses in Sakata City Fire is $130{,}845\mathrm{m}^2$ as shown in TABLE 1, so the total quantity of combustibles in the burnt floor area is estimated as $130{,}845 \times 120 \approx 15{,}700{,}000\,\mathrm{kg}$.

Although the Sakata City Fire lasted for eleven hours from the fire spreading chart Fig.1., it is known that about 90% of the houses burnt out in about seven hours from 8 p.m. to 3 a.m., next morning. So it follows that the number of houses burnt per hour is $(1{,}673 \times 0.9)/7 = 215$ houses/hour in average.

Therefore, the mass burning rate of wood in the same period is estimated as $(15{,}700{,}000 \times 0.9)/(7 \times 3{,}600) \approx 561\,\mathrm{kg}/\mathrm{s}$. According to the BRI house burn test [6], the mass burning rate per floor area of house is estimated as $0.1\mathrm{kg}/\mathrm{m}^2 \cdot \mathrm{s}$, so the floor area burning at a certain moment is $561/0.1 = 5{,}610\,\mathrm{m}^2$. In Sakata City Fire, the average floor area of the houses in the area was $78\,\mathrm{m}^2/\mathrm{house}$ in TABLE 1, hence the number of houses burning at the same moment $5{,}610/78 \approx 72\mathrm{houses}$.

Therefore the average duration of the burning of a house t_d, which is used in Eq.(8), is estimated as

$$t_d = 72/215 \approx 1/3\,\mathrm{hour} = 20\mathrm{min} \qquad (9)$$

3.5 THE OUTBREAK OF FIRE BY FIREBRANDS

In an urban fire and a post-earthquake fire, firebrands produced by the fire cause multiple fires. There was a fire source originated by fire brands in Sakata City Fire as well. The brands fires can be dealt with easily by calculating $Tmesh(k,l)$ for each fire source and the value of $Mflag(k,l)$ using Eq.(8).

4. ESTIMATION OF TEMPERATURE RISE DUE TO FIRE FLOW

Considering the effect of the heat flow for a point on the ground surface, the temperature is most potently influenced by the burning of the areas at straight upstream of the target point, and the more deviate the area from the direct upstream the less strongly. However theoretically the point is more or less affected by all burning areas. Therefore the effect of all the meshes burning on an arbitrary location has to be taken into account in the estimation.

4.1 HEAT RELEASE RATE

Assuming that the mass burning rate per floor area of house be $0.1\mathrm{kg}/\mathrm{m}^2 \cdot \mathrm{s}$ based on the full scale experiment conducted at Building Research Institute [6] and the effective calorific value of wood be $16{,}000\,\mathrm{kJ}/\mathrm{kg}$, the heat release rate Q per floor area can be calculated as

$$Q = 16{,}000 \times 0.1 = 1{,}600 \ \mathrm{kW/m^2} \tag{10}$$

The proportion of the floor area of houses devastated by the fire to the total urban city area is $S(2)/S(1)$, where $S(1)$ is the burnt area in urban district, $S(2)$ is the floor area of wooden buildings. Hence in the case where the burning area is liner, the heat release rate per the unit length of burning mesh Q_1 can be written as

$$Q_1 = 1{,}600 \times \frac{S(2)}{S(1)} \times D_m \ \mathrm{kW/m} \tag{11}$$

where D_m is the mesh width. The heat release rate per the unit area of burning area Q_2 can be expressed as follows

$$Q_2 = 1{,}600 \times \frac{S(2)}{S(1)} \times A_m \ \mathrm{kW} \tag{12}$$

where A_m is the mesh area. In case of Sakata City Fire, the value of $S(1)$ and $S(2)$ is given in TABLE 1 as follows.

$$S(1) = 225{,}000 \ \mathrm{m}^2 \qquad \text{and} \qquad S(2) = 130{,}824 \ \mathrm{m}^2$$

In this study, $5\mathrm{m} \times 5\mathrm{m}$ size mesh is adopted. The values of the heat release rates Q_1 and Q_2 are given as follows

$$Q_1 = 1{,}600 \times \frac{130{,}824}{225{,}000} \times 5 \approx 4650 \ \mathrm{kW/m} \tag{13}$$

$$Q_2 = 1{,}600 \times \frac{130{,}824}{225{,}000} \times 25 \approx 23{,}300 \ \mathrm{kW} \tag{14}$$

4.2 TEMPERATURE RISE ALONG THE PLUME AXIS OF A FINITE FIRE SOURCE

It is known that the average temperature rise along the axis of fire plume from a fire source with finite size in calm environment is given as follows

$$\Delta T_0 = \begin{cases} 900 & \left(z/Q_2^{2/5} < 0.08\right) \\ 60\left(z/Q_2^{2/5}\right)^{-1} & \left(0.08 < z/Q_2^{2/5} < 0.2\right) \\ 24\left(z/Q_2^{2/5}\right)^{-5/3} & \left(0.2 < z/Q_2^{2/5}\right) \end{cases} \tag{15}$$

where z is height from fire source on the plume axis. [6]

It is known that the temperature of a vertical fire plume shows approximately Gaussian distribution in horizontal direction, so the temperature rise at the distance r from the axis $\Delta T(r)$ can be given by the following equation.

$$\frac{\Delta T(r)}{\Delta T_0} = \exp\left\{-\boldsymbol{b}\left(\frac{r}{b}\right)^2\right\} \tag{16}$$

where b is the half-width of a fire plume and $\boldsymbol{b}$ is the ratio of half-width of temperature to that of flow velocity. The value of b is approximated as $b = 0.1z$ and $\boldsymbol{b} = 1$ on the basis of the existing study on fire plume. It is not clear if the temperature rise in wind-blown plume is similar with Eqs.(15) and (16). For the first order approximation, it is assumed here that the temperature rise along the axis of the wind-blown fire is the same as vertical fire plume.

4.3 DIRECTIONAL VECTOR OF FIRE PLUME AXIS

- **GRADIENT OF FIRE PLUME AXIS**

From the wind tunnel experiment by Yokoi, the gradient of a wind-blown plume axis in case of a line fire source is given as

$$\tan\theta = 0.1\Omega^{-3/4} \tag{17}$$

where Ω is the dimensionless velocity of the wind defined as

$$\Omega = \frac{U_\infty}{\left(\dfrac{Q_1' g}{\rho_\infty c_p T_\infty}\right)^{1/3}} \approx 3.3\left(\frac{U_\infty}{Q_1'^{\,1/3}}\right) \tag{18}$$

where c_p is the constant-pressure specific heat, ρ_∞ is the ambient air density, T_∞ is the ambient temperature, g is the acceleration due to gravity and U_∞ is the representative wind velocity.

- **DIRECTIONAL VECTOR OF WIND**

Letting α be the angel of wind direction from west-east coordinate of the city map, the directional vector of the wind is $(\cos\alpha, \sin\alpha)$. Incidentally, where the coordinates of a specific map used happen to be deviate from the geographical direction, α needs to be adjusted as

$$\alpha = \alpha_1 + \alpha_2 \tag{19}$$

where with plus α_1 is the angle between the axis of map and geographical direction α_2 is the angle formed by the direction of wind to the eastern and western direction, the angle between x axis and the wind direction α is as shown in Fig.4-(a)..

- **DIRECTIONAL VECTOR OF FIRE PLUME AXIS**

Thus the directional vector $\mathbf{a}$ of fire plume axis with wind direction $(\cos\alpha, \sin\alpha)$ and a rising angle due to buoyancy θ, is given as by using Eq.(19) as shown in Fig.4-(b).

$$\mathbf{a} = (\cos\alpha, \sin\alpha, \tan\theta) \tag{20}$$

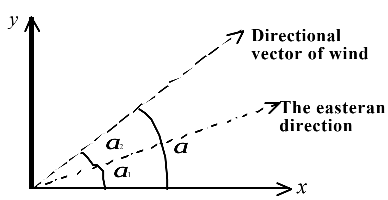


Fig.4-(a): Angle of directional vector of wind

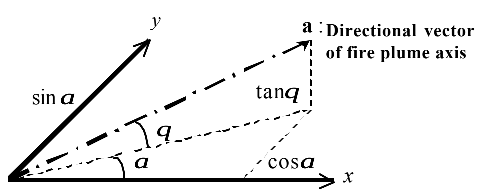


Fig.4-(b): Directional vector of fire plume axis

4.4 TEMPERATURE RISE DUE TO THE FIRE PLUME OF SINGULAR FIRE SOURCE

Fig.5. shows location of a fire plume axis that rises from a burning mesh and a target mesh. In this figure, the length corresponding to z in Eq.(15) for the temperature rise on the plume axis is the length on the plume axis. That is to say

$$z = \left|\overrightarrow{P_o}\right| \tag{21}$$

where $\vec{P_o}$ is a vector of the foot of a perpendicular drawn from G_b, the center of the target mesh (k_b, l_b), i.e. $\{gx(k_b), gy(l_b)\}$, to the plume axis. And the length corresponding to r in Eq.(16) for the temperature rise at off the plume axis is the length of the segment drawn vertically from G_b to the axis i.e.

$$r = \left|\overrightarrow{G_0} - \overrightarrow{P_0}\right| \tag{22}$$

where $\vec{G_0}$ is the position vector of G_b relative to the center of the burning mesh(k_u, l_u) $\{gx(k_u), gy(l_u)\}$.

Using a scalar parameter h and the dimensional directional vector of fire plume axis $\mathbf{a}$, $\vec{P_o}$ is given as $\overrightarrow{P_o} = h \cdot \mathbf{a}$. Since the fire plume axis and the line $\overline{G_b P_o}$ cross with a right angle, substituting $\overrightarrow{P_o} = h \cdot \mathbf{a}$ in $(\overrightarrow{G_0} - \overrightarrow{P_o}, \mathbf{a}) = 0$ and solving it for parameter h, we have $h = (\overrightarrow{G_o}, \mathbf{a}) / |\mathbf{a}|^2$. Therefore the length $z = \overline{G_u P_o}$ is given as

$$z = \overline{G_u P_o} = \left|\overrightarrow{P_o}\right| = h|\mathbf{a}| = \frac{\left|(\vec{G_o}, \mathbf{a})\right|}{|\mathbf{a}|} \tag{23}$$

And the length $r = \overline{G_b P_o}$ is given as

$$r = \overline{G_b P_o} = \left|\overrightarrow{G_0} - \overrightarrow{P_0}\right| = \sqrt{\left|\overrightarrow{G_o}\right|^2 - \frac{(\overrightarrow{G_o}, \mathbf{a})^2}{|\mathbf{a}|^2}} \tag{24}$$

The values of $\left|\vec{G_0}\right|^2$, $(\vec{G_0}, \mathbf{a})$, $|\mathbf{a}|$ in Eqs.(23) and (24) can be given as

$$\left|\vec{G_0}\right|^2 = \left(gx(k_u) - gx(k_b)\right)^2 + \left(gy(l_u) - gy(l_b)\right)^2 \tag{25}$$

$$(\overrightarrow{G_0}, \mathbf{a}) = \left(gx(k_u) - gx(k_b)\right) \times \cos \boldsymbol{q} + \left(gy(l_u) - gy(l_b)\right) \times \sin \boldsymbol{q} \tag{26}$$

$$|\mathbf{a}| = \sqrt{1 + \tan^2 \boldsymbol{q}} \tag{27}$$

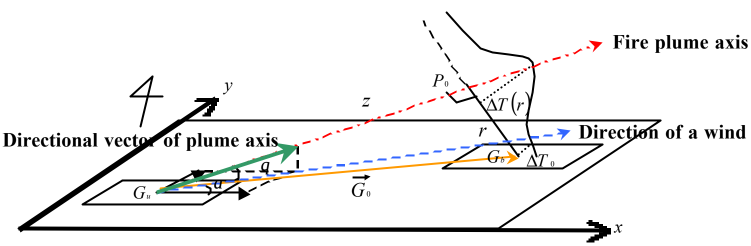


Fig.5: Location of a fire plume axis that rises from a burning mesh and a target mesh

4.5 TEMPERATURE RISE DUE TO THE FIRE PLUME OF PLURAL FIRE SOURCES

In an actual fire, the values of z and r for a specific mesh change with the locations of the heat source mesh and the target mesh so the temperature rise varies accordingly. Considering that the number of burning mesh is N in general, the temperature rise of a target mesh due to the effect of fire plume from source mesh i, ΔT_i, is calculated by Eqs.(15) and (16). However, a target mesh can be affected by multiple heat source meshes, that are under burning, so in general the total temperature rise at a target mesh ΔT must be calculated taking into account the effect of all the meshes set in the city area. In this paper, the temperature rise under this condition is calculated by

$$\Delta T = \left\{ \sum_{i=1}^{N} \left(\Delta T_i \right)^{3/2} \right\}^{2/3} \tag{28}$$

Although the work for validation of Eq.(28) is limited, this formula is theoretically valid for the extreme cases: i.e. the sources are very close or very remote.

5. RESULTS AND CONSIDERATION OF THE SAKATA CITY FIRE

Using the model described in the above, we estimate the hazard due to wind–blown fire flow induced by the Sakata City Fire. The conditions of the houses in the area and the fire spreading conditions were estimated from the data shown in TABLE 1 and Fig.1. The velocity and direction of wind, the temperature and the humility was taken from the data measured by the weather observatory in Sakata, which is shown in TABLE 2.

TABLE 2: Weather condition in Sakata City

DATA	VELOCITY OF WIND (m/s)	DIRECTION OF WIND	TEMPERATURE (℃)
5 p.m., 10/29	11.7	W	8.0
6 p.m.	12.2	WSW	8.5
7 p.m.	11.1	W	9.1
8 p.m.	9.0	WNW	9.2
9 p.m.	12.0	WNW	9.9
10 p.m.	12.4	WNW	10.1
11 p.m.	10.0	WNW	8.9
0 a.m., 10/30	11.5	WNW	9.2
1 a.m.	12.3	WNW	8.9
2 a.m.	11.7	WNW	9.3
3 a.m.	10.8	WNW	8.9
4 a.m.	9.3	WNW	9.4

5.1 RESULTS

Fig.6. shows the area of burning and the areas at different temperature rise, which are distinguished by darkness level. The darkest gray part stands for the area under burning, the black area is already burnt down and the parts indicating by dark gray to light gray are the area exposed to fire flow at different temperature depending on darkness level. As can be seen in Fig.6, the area affected by fire flow is much wider than the area that is actually burning.

The people in some part of this area were ordered to evacuate their houses during the period of the fire. The area enclosed by dashed black lines in Fig.6. is the area where the evacuation order was issued. The actual situation of evacuation of city residents in Sakata City Fire were investigated by the questionnaire conducted by Building Research Institute on the people whose houses were burnt [7]. In the questionnaire, the people were asked when they felt the situation was dangerous and when they started to evacuate. The results are shown in TABLE 3. In average, the people started to evacuate their houses at 1h 22min. ahead of the time igniting their own houses. The black lines in Fig.6., which were generated on the basis of the questionnaire survey [7], show the border lines in which the people judged that they were in danger caused by spreading fire and started to evacuate at a given time. It is known that people started to evacuate earlier at the late period than the early period of the fire.

5.2 CONSIDERATION

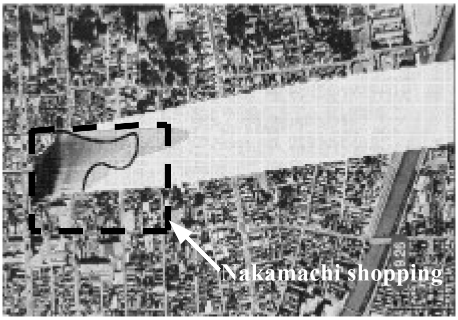
Although this estimation is a little rough, the following things are thought from the above results.

In the Sakata City Fire, the residents in Nakamachi shopping district, which is enclosed by dashed black lines in Fig.6-(a)., were ordered to evacuate at 7:58 p.m. As compared with the burning area, Nakamachi shopping district is still far away from the burning area as yet at eight o'clock in the afternoon. Around this stage, the highest temperature rise estimated at this district is over 100℃ as shown in Fig.6-(a)., so it is suspected this district was about to be exposed to fairy dangerous smoke depending on the direction and velocity of wind. It is suspected that the evacuation order at Sakata City Fire issued in consideration of the occurrence of the dangerous condition due to a fire flow like this.

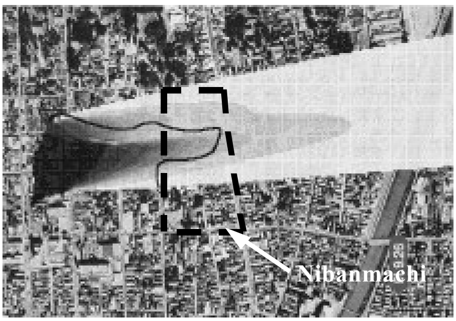
The residents in another area, Nibanmachi area district which is enclosed by dashed black lines in Fig.6-(b)., were ordered to evacuate at 9:30 p.m. The highest temperature rise in this area was about 75℃ at 9 p.m. as shown in Fig.6-(b)., and this area was involved in the fire at 10 p.m. in Fig.6-(c)., so it is considered that this district was at very dangerous condition. It may be that the evacuation order should have been issued a little earlier.

TABLE 3: The elapsed time at which the people in Sakata started to evacuate since they felt the situation was dangerous

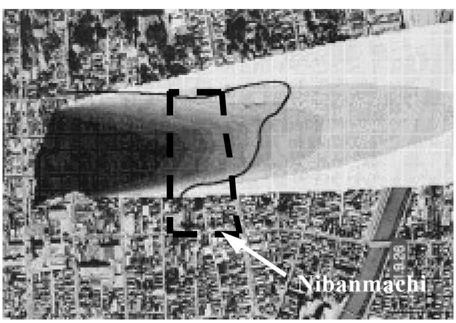
PLASE	TIME
Nakamachi 2	53 minuites
Nakamachi 1	50 minuites
Nibanmachi	an hour and 13 minutes
Ichibanmachi	an hour and 20 minutes
Niidamachi	2 hours and 2 minutes



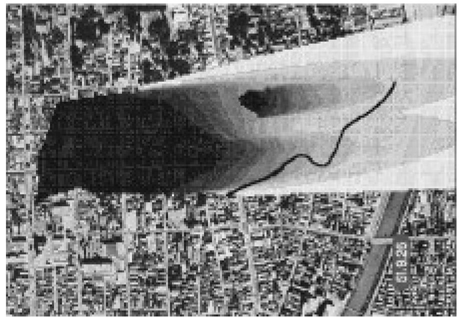
(a): After 140 minutes from the onset of fire (8 p.m. 10/29)



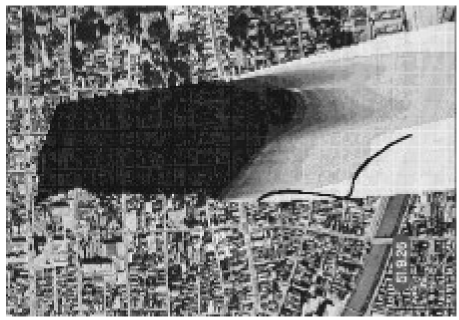
(b): After 200 minutes from the onset of fire (9 p.m. 10/29)



(c): After 260 minutes from the onset of fire (10 p.m. 10/29)



(d): After 320 minutes from the onset of fire (11 p.m. 10/30)



(e): After 380 minutes from the onset of fire (0 a.m. 10/30)

- Burning Area
- Burnt Area
- Temperature Rise:1～10℃
- Temperature Rise:10～20℃
- Temperature Rise:20～30℃
- Temperature Rise:30～40℃
- Temperature Rise:40～50℃
- Temperature Rise:50～75℃
- Temperature Rise:75～100℃
- Temperature Rise:over 100℃
- **Border line in which the people started to evacuate**

Fig.6: The temperature rise and the state of combustion

6. CONCLUSION

The method to estimate the temperature rise in the down stream area of urban fire was developed to analyze the problems of residents' evacuation in urban fire, and the estimated hazard due to the exposure to fire is compared with the evacuation start time of the residents in Sakata City Fire.

In future, by combining the hazard estimation by this method and some adequate evacuation model, the authors would like to analyze the problems concerning evacuation in case of urban fires in the past and in contemporary city. To do this, the followings should be considered to improve the estimation of the hazard:

a) In this paper, an urban district is treated as uniform and heat release rate is constant. But as the building-to-land ratio becomes higher, heat release rate may become larger. So it must be considered how the structures of an urban district such as the building-to-land ratio, roads, and so on affects heat release rate.
b) The gradient of a plume axis is based on the results of experiment for a line heat source, for there is few study for the plume from a plane heat source. It will be necessary to replace the model for the plume gradient as the study progresses on plumes of plane heat sources.
c) The heat release from a mesh where the houses have burnt out was ignored, but it is considered that the mesh still release a considerable heat by virtue of the burning debris.

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