화재실험시 열유속 센서 사용의 단점을 보완한 Heat Flux Mapping Procedure에 관한 연구

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A Study of a Heat Flux Mapping Procedure to Overcome the Limitation of Heat Flux Gauges in Fire Tests

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Abstract : It is essential to understand the role of wall lining materials when they are exposed to a fire from an ignition source. Full – scale test methods permit an assessment of the performance of a wall lining material. Fire growth models have been developed due to the costly expense associated with full – scale testing. The models require heat flux maps from the ignition burner flame as input data. Work to date was impeded by a lack of detailed spatial characterization of the heat flux maps due to the use of limited instrumentation. To increase the power of fire modeling, accurate and detailed heat flux maps from the ignition burner are essential. High level spatial resolution for surface temperature can be provided from an infrared camera. The objective of this study was to develop a heat flux mapping procedure for a room test burner flame to a wall configuration with surface temperature information taken from an infrared camera. A prototype experiment was performed using the ISO 9705 test burner to demonstrate the developed heat flux mapping procedure. The results of the experiment allow the heat flux and spatial resolutions of the method to be determined and compared to the methods currently available.

초록 : 건물의 마감재료가 화재에 노출될 때 그 마감재료의 역할을 이해하는 것은 필수적이다. 실물화재실험을 통해서 재료의 성능을 평가하는 것이 가능하다. 그러나 실물화재 실험 시 소요되는 시간과 높은 비용으로 인해 실물화재 실험이 수행되는 경우는 드물고 대신 컴퓨터 화재 시뮬레이션이 개발되어 왔다. 컴퓨터 화재 시뮬레이션에서는 초기입력 데이터로서 점화 버너의 화염으로부터의 Heat Flux Map이 요구된다. 현재까지의 연구에서는 열전대 혹은 열유속 센서와 같은 실험장치의 제한으로 인해 10kW/m^2 간격의 Heat Flux Map이 나와있을 뿐이고 공간적으로 더 상세한 Heat Flux Map은 없는 실정이다. 화재 시뮬레이션의 성능을 증가시키기 위해서는 점화 버너로부터의 정확하고 상세한 Heat Flux Map이 필요불가결하다. 본 연구의 목적은 적외선 카메라로부터 얻어진 표면온도를 이용하여 벽에서 점화 버너 화염에 대한 Heat Flux Mapping Procedure를 개발하는 것이다. 높은 수준의 공간적 해상도는 적외선 카메라로부터 제공된다. 개발된 Heat Flux Mapping Procedure를 증명하기 위해서 ISO 9705 점화버너를 이용해서 실험이 행해졌다. 실험 결과를 통해 개발된 Heat Flux Mapping 방법의 열유속 해상도와 공간적 해상도가 얻어졌다. 또한 그 실험 결과가 현재 쓰여지고 있는 Heat Flux Map과 비교되었다.

Key Words : fire modeling, heat conduction model, heat flux mapping procedure, heat flux maps, infrared camera

Nomenclature

c	heat capacity at constant pressure [J/kgK]
h_c	convective heat transfer coefficient [kW/m^2K]
k	thermal conductivity [W/mK]
$\dot{q}''_{net}$	net heat flux [kW/m^2]
T_0	initial temperature [K]
T_H	Cone heater temperature [K]
T_s	surface temperature [K]

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T_∞ ambient temperature [K]
t time [s]
y distance perpendicular to surface [m]
ε_s emissivity of surface [−−]
ρ density [kg/m^3]
σ Stefan-Boltzmann constant [$5.67\times10^{-11} kW/m^2K^4$]

1. Introduction

Accurate fire growth predictions using models such as flame spread algorithms are very important for the evaluation of the performance of wall lining materials in fire. The algorithms require heat flux maps provided by an ignition burner flame. However, few studies have been done and the works to date have limitations in terms of spatial resolution. To increase the power of fire modeling, the accurate and detailed heat flux maps from the ignition burner are critical.

The objective of this research is to develop a heat flux mapping procedure for a room test burner flame to a wall lining material with the information of surface cooling temperature taken from an infrared camera. One − dimensional (1D) heat conduction model is developed for heat flux mapping from the burner. The resolution of the model can be obtained utilizing 1D temperature data from the Cone Calorimeter tests. It is valuable that the infrared camera can provide high level spatial resolution for surface temperature.

2. Literature Review

2.1. Requirement of Flame Spread Models

It is very important to understand the performance of wall lining materials in room fire development. ISO 9705 room/corner test[1] is used for the classification of wall linings. Due to the costly expense associated with full − scale testing, there is significant interest in simulating full − scale tests based on the results from bench − scale test apparatus such as the Cone Calorimeter[2]. Several flame spread algorithms to predict the results of the ISO 9705 test[1] are available with different levels of complexity by Karlsson[3], Janssens *et al.*[4], Wright[5], and Lattimer *et al.*[6]. Those flame spread algorithms require heat flux information from the ignition burner flame. Heat flux from the burner was assumed constant by Karlsson[3] and Janssens *et al.*[4] Wright[5] has taken experimental information on the heat flux distribution from Dillon's work[7]. In the case of Lattimer *et al.*[6], heat flux mapping experiments were conducted to develop heat flux correlations for use in the model. To make the algorithms more robust, it is essential to provide accurate and detailed heat flux maps.

2.2. Previous Studies on Heat Flux from the Ignition Burner Flame

Few studies have been carried out to determine the incident heat flux from the ignition burner. Janssens[4,8] determined heat flux values based on the heat output of the burner and the temperature of the material. Back *et al.*[9] measured incident wall heat flux distributions on a flat wall configuration with the measurements in 0.15m increments. Correlation of data for the measured heat flux distributions were developed for wall flame spread modeling. Williamson *et al.*[10] conducted room/corner experiments to evaluate the effects of ignition source intensity and location on the heat flux distribution.

Kokkala[11] performed experiments for total heat flux distributions in an open corner of walls and the contour plots for the flux distributions were based on 100 data points. The flux distributions indicate lines of constant heat flux in 10kW/m^2 increments. Dillon[7] provided heat flux distributions along the walls and ceiling at every 10kW/m^2. A total of 96 thermocouples were used at intervals of 0.15m. Lattimer *et al.*[6] conducted tests using the full − scale mock corner with an overhead. The heat flux measurements were taken from twenty heat flux gauges placed 0.15m or 0.3m apart.

3. Development of a Heat Flux Mapping Procedure Utilizing an Infrared Camera

A standard room test burner, the ISO 9705 burner[1], is turned on for a certain duration with a known heat release rate, $\dot{Q}$, in a flat wall configuration. A schematic of the experimental set up is illustrated in Fig. 1. One temperature measurement in depth is taken at

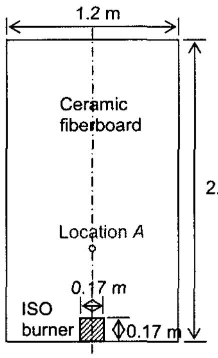

Fig. 1. A schematic of the experimental set up with a standard room test burner in a flat wall configuration.

a location using a thermocouple. For the purpose of explanation this location is called "Location *A*" for convenience. Immediately after the burner is turned off, an infrared camera takes the cooling temperature histories over the surface area including surface temperature at Location *A*. Correct surface temperature data for the heating period cannot be obtained with an infrared camera due to the presence of the soot in the diffusion flames. However, the surface temperature data when the flame is removed, *i.e.*, in the cooling period, can be utilized to determine the incident heat flux from the burner flame. Considering the fact that an infrared camera has high level spatial resolution, surface temperature measurements can be taken at numerous locations. This database of empirical results is used for comparison to a heat conduction model.

One – dimensional (1D) heat conduction model was developed for heat flux mapping from the ignition burner. One might question that solving the 1D heat conduction equation is oversimplified to predict temperature profiles. However, it is reasonable considering the material used, ceramic fiberboard, is an inert material. It is essential that the heat conduction model uses actual thermal properties of the material such as thermal conductivity, specific heat, and emissivity as opposed to generic values. The use of actual thermal properties is directly related to the accuracy of temperature prediction from the model. The model is run with appropriate thermal properties and can provide temperature profiles not only in depth but also at the surface. Each run is made with a given incident heat flux and burner exposure duration.

This model requires the thermal response of the wall lining material which is calibrated using Cone Calorimeter. The 1D temperature data taken from the Cone Calorimeter tests are simulated by the model. It is obvious that the simulated temperature data from the 1D model have to be compared with the measured temperature data from the Cone specimen which shows a 1D heat transfer behavior. It is pointless to compare the 1D simulated data with 2D or 3D measured data in the Cone. It was found out that the current Cone specimen preparations, *i.e.*, the 100mm by 100mm specimen size regardless of whether the retainer frame is used or not, result in 3D behavior with ceramic fiberboard[12]. Obtaining 1D temperature data from the Cone tests was studied by Choi[12].

In order for the 1D model to reproduce the temperature data measured in depth at Location A, the model is repeatedly run for the same exposure time as in the experiment by varying the incident heat flux only. Once the modeled temperature history agrees with the measured one in depth at Location A, the incident heat flux used in the model is determined as a best estimate heat flux from the ignition burner for Location *A*. Cooling surface temperature history taken from the infrared camera at Location *A* is then compared with the one from the model under the determined incident heat flux. Residual between the measured surface temperature and the simulated surface temperature at Location *A* is calculated. It is the procedure to determine the residual for a best estimate heat flux.

Using the residual at Location *A* as matching criteria for heat flux, other heat fluxes for other locations are determined by comparing cooling surface temperature histories from the infrared camera with the ones from the model. All the heat fluxes at all locations create the heat flux map.

4. One – Dimensional Heat Conduction Model

4.1. Development of the One – Dimensional Heat Conduction Model

The model solves the one – dimensional heat conduction equation for a semi-infinite solid. The governing equation is

$$\rho \frac{\partial}{\partial t}\left(c(T)T\right) = \frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right) \tag{1}$$

The initial and boundary conditions are as follows.

$$t = 0, \qquad T = T_0 \tag{2}$$

$$y = 0, \; -k\frac{\partial T}{\partial y} = \dot{q}''_{net} = \frac{F_{s-H}\varepsilon_s \sigma (T_H^4 - T_s^4)}{\varepsilon_s + F_{s-H}(1-\varepsilon_s)} - h_c(T_s - T_0) \tag{3}$$

$$y = \infty, \qquad T = T_\infty \tag{4}$$

The density, ρ, of the ceramic fiberboard does not change significantly with temperature. But the thermal conductivity, k, and specific heat, c, of the ceramic fiberboard are a function of temperature. The temperature dependent thermal conductivity, $k(T)$, and the specific heat, $c(T)$, were provided by the manufacturer, Thermal Ceramics Inc. The emissivity of surface, ε_s, was measured using the infrared camera.

4.2. Resolution of the Developed One – Dimensional Heat Conduction Model

The 1D model simulated temperatures from Cone Calorimeter tests and the results between experiment and calculation were compared. The varying parameter of this model was incident heat flux such that each run of the model gave a different predicted temperature profile with time. This temperature profile was then compared with the profile from Cone Calorimeter test until a match is made. According to Choi's study[12)], the 178mm by 178mm ceramic fiberboard specimen provides the best result in terms of approximating 1D heat conduction in the Cone Calorimeter compared to temperature profiles from a current standard specimen preparation. Thus, the simulated temperature profiles from the 1D model were compared with the Cone data using the 178mm by 178mm specimen.

Fig. 2 shows the comparison of the experimental and calculated temperature histories in depth when the incident heat flux, 40kW/m^2, was applied. The temperature profiles from the 1D model agree favorably with the 1D temperature data from the Cone Calorimeter test. Through the comparison the resolution of the 1D model, ±1kW/m^2, was obtained.

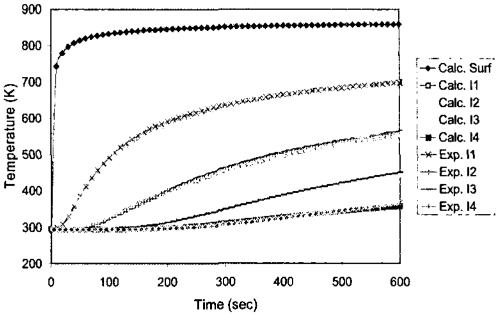

Fig. 2. Comparison of the simulated data from the 1D model with the measured 1D data from the Cone test for 40 kW/m^2.

4.3. Application of a 1D Heat Conduction Model on Determining Heat Fluxes from a Real Fire Situation

The advantage of using the 1D "direct" approach is that the mathematical complexities and difficulties associated with 3D and 1D "inverse" codes are avoided. To validate the use of a 1D model to determine heat fluxes from a real fire situation, a commercial 3D conduction code, ALGOR's finite element analysis,13 has been used for the purpose of comparison.

Transient heat transfer in ALGOR's finite element analysis was used with the same properties as in the 1D model. Temperature distribution at each time step was obtained through the ALGOR run. As an example of results, surface temperature profiles computed at 5 seconds are shown in Fig. 3. It was expected that the temperature profile would show smooth transition from high to low temperatures. However, inconsistent temperatures were observed in Fig. 3. Some of distinguished ones are marked with oval. These inconsistent temperature profiles would not occur in reality. It was discovered through the communication with technical support in ALGOR that the computational limitation of ALGOR software could cause the inconsistent temperature profiles to show up.

Due to the unrealistic temperature profiles shown above, 2D analyses in ALGOR were done using a thin strip shape. The temperature data from 2D analyses as a vertical and a horizontal strip were compared with data from 1D analysis. It is acceptable to use the developed 1D heat conduction model in the area of the center line above the burner in the prototype experiment which showed 1D behavior through ALGOR runs.

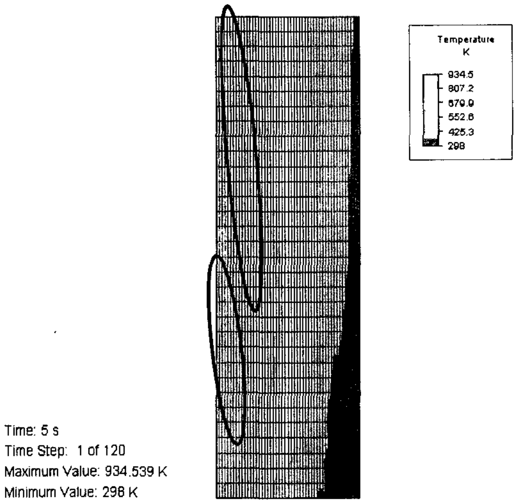

Fig. 3. Result from 3D ALGOR run using Lattimer's heat flux distribution – surface temperature profile at 5 seconds.

5. Prototype Experiment Utilizing an Infrared Camera

5.1. Experimental Setup

To demonstrate how the method described in Section 3 works, a series of prototype experiments were conducted using an infrared camera. The infrared camera[14] provides high level spatial resolution for surface temperature compared to using thermocouples or heat flux gauges. If the infrared camera is placed 150cm away from a target, 1cm spatial resolution can be obtained.

The experiment was performed in a wall configuration using the ISO 9705 test burner[1]. For simplicity a flat wall configuration was used with five layers of 6.35mm thick ceramic fiberboard on top of two layers of 12.7mm thick ceramic fiberboard. First interface between first layer and second layer is called I1. A schematic of the experimental set up with a standard room test burner in a flat wall configuration is shown in Fig. 1. One Schmidt-Boelter heat flux gauge was used to compare the heat flux determined through the heat flux mapping procedure. A total of twenty five thermocouples were installed in the vicinity of the thermocouple at Location *A* to confirm that measured temperature data in the area are almost same as the temperature data at Location *A*.

Fig. 4. Prototype experiment in a wall configuration with a room test burner – Front view in the heating period.

5.2. Prototype Experiment Utilizing an Infrared Camera

The goal of the prototype experiment is to show if higher spatial resolution than currently available can be obtained for heat flux. The current heat flux distribution specifies lines of constant heat flux in 10 kW/m^2 increments. For the purpose of the experiment the ISO 9705 burner[1] was turned on for 5minutes to heat up the ceramic fiberboard at heat release rate of 50kW. Fig. 4 shows the front view of the experiment for the heating period.

Temperature measurement at the depth of I1 was taken at Location *A* using a thermocouple. Immediately after the fire source was removed, *i.e.*, after 5 minutes, the infrared camera started to capture the surface temperature data of the heated wall material including surface temperature at Location *A*. Cooling surface temperature data were measured from the infrared camera at numerous locations for another 5minutes.

One Schmidt-Boelter heat flux gauge was used on the wall for the purpose of comparison of the heat flux measurement with the determined one through the heat flux mapping procedure. The measurement from the heat flux gauge was taken at every one second. The measured data showed a significant fluctuation between mainly 20 and 40kW/m^2. Due to the large variation, the average heat flux, 28kW/m^2, was calculated. Based upon the correlation of the heat flux measurement in the Cone Calorimeter between with and without ceramic fiberboard[12], the heat flux, 28 kW/m^2, was decreased by 15%, which is equal to 23.8kW/m^2. The uncertainty of ±3% was reported by the manufacturer, which corresponds to a range of 23 to 24.5kW/m^2 for the heat flux measurement. This range of 23 to 24.5kW/m^2 from the Schmidt-Boelter heat flux gauge is then compared with the heat flux from the heat flux mapping procedure.

For Location A, the temperature measured at the depth of I1 was compared with the one from the 1D model by varying the incident heat fluxes (Fig. 5). In case that the incident heat flux, 21kW/m^2, was applied in the model, the simulated temperature agreed favorably with the measured temperature based on the values of the average temperature difference and residual as shown in Table 1. Since a match was found between measurement and simulation, the incident heat flux used in the model, 21kW/m^2, was determined as a best estimate heat flux from the ignition burner for Location A.

Considering the uncertainty of the model, ±1kW/m^2, as mentioned in Section 4.2, the determined heat flux from the model should be expressed as a range of 20 to 22kW/m^2. This range of heat flux matches

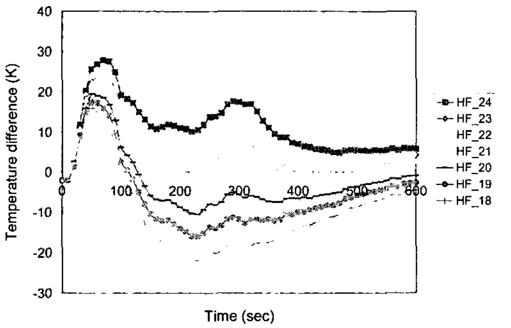

Fig. 5. Comparison of the temperature differences between the measured temperature data and the simulated data with various heat fluxes at the depth of I1.

Table 1. Comparison of the temperature difference between the measured temperature data and the simulated data with various heat fluxes from 18 to 24kW/m^2

IHF	18 kW/m^2	19 kW/m^2	20 kW/m^2	21 kW/m^2	22 kW/m^2	23 kW/m^2	24 kW/m^2
Avg. ΔT (K)	-13.5	-9.2	-5.2	-1.1	2.7	6.4	9.9
Residual (K)	2.2	1.6	0.9	0.3	0.4	1.0	1.5

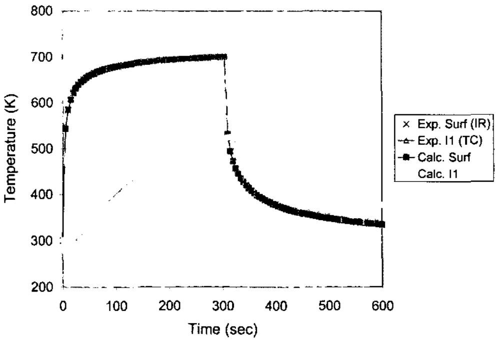

Fig. 6. Comparison of the measured temperature data with the simulated data for the incident heat flux, 21kW/m^2.

reasonably well with the measurement from the Schmidt-Boelter heat flux gauge, 23 to 24.5kW/m^2, considering the large variation between 20 and 40kW/m^2.

Since the incident heat flux was determined at Location A, surface temperature history can be obtained from the model. Cooling surface temperature data recorded from the infrared camera at Location A was compared with the one from the model (Fig. 6). It is observed that the simulated surface temperature drops too quickly after the burner was turned off and then near the end of the cooling period the modeled data match the data from the infrared camera.

It was investigated why the surface temperature from the model decreases so rapidly. The 1D heat conduction model was examined thoroughly to see if the model has an error or if a unknown parameter from the experiment was not accounted for in the model. However, nothing was found in regard of the model. It made question if the surface temperature data from the infrared camera were accurate as they occurred on the wall in reality. It is noted that the infrared camera was calibrated at the manufacturer before it was used in the experiment. In general the response time of the camera is fast. It was found out that the discrepancy between the measurements from the infrared camera and the results from the model during the cooling period was due to a limitation of the infrared camera used in the experiment.

At Location A the measured cooling temperature data and the simulated cooling data for 21kW/m^2 were used to calculate a residual using Equation 5. Note that N is a number of data. The number of data is

30 since the cooling data from the infrared camera at every 10 seconds from 310 to 600 seconds were used. The value of 4 K for a residual at Location *A* was acquired from Equation 5 and was used as matching criteria for determining heat flux along the center line above the burner. The choice of the residual, 4 K, resulted from the temperature measurement accuracy of the infrared camera, ±2℃ or ±2%. It is noted that using the "later" times when the infrared camera has caught up for surface temperature from the model is not the best way to develop the residual for heat flux. The residual from using "later" times was in fact inferior to the residual of 4 K because all of the residuals from 18 to 24kW/m^2 were less than 3 K which is under the uncertainty of the infrared camera measurements.

$$E_{rms} = \frac{\sqrt{\sum (T_{\exp} - T_{calc})^2}}{N} \tag{5}$$

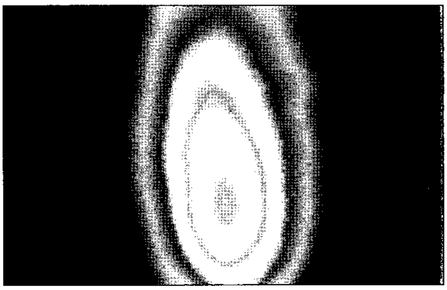

Fig. 7. An overall infrared image of the heated wall after the burner was turned off.

Distance from burner (m)	Determined heat flux (kW/m^2)	Distance from burner (m)	Determined heat flux (kW/m^2)	Distance from burner (m)	Determined heat flux (kW/m^2)	Distance from burner (m)	Determined heat flux (kW/m^2)
0.8	**3**	**0.6**	**9**	**0.4**	**21**	**0.2**	**14**
0.79	3	0.59	10	0.39	18	0.19	12
0.78	3	0.58	10	0.38	19	0.18	12
0.77	3	0.57	11	0.37	21	0.17	11
0.76	4	0.56	11	0.36	20	0.16	11
0.75	3	0.55	11	0.35	19	0.15	10
0.74	4	0.54	12	0.34	20	0.14	10
0.73	4	0.53	12	0.33	19	0.13	8
0.72	5	0.52	12	0.32	19	0.12	8
0.71	5	0.51	13	0.31	19	0.11	7
0.7	**5**	**0.5**	**13**	**0.3**	**19**	**0.1**	**6**
0.69	5	0.49	13	0.29	19	0.09	5
0.68	5	0.48	14	0.28	18	0.08	6
0.67	6	0.47	15	0.27	17	0.07	4
0.66	6	0.46	14	0.26	19	0.06	4
0.65	6	0.45	17	0.25	17	0.05	3
0.64	7	0.44	15	0.24	16	0.04	3
0.63	8	0.43	17	0.23	15	0.03	2
0.62	9	0.42	19	0.22	15	0.02	2
0.61	9	0.41	17	0.21	14	0.01	1

Fig. 8. Heat flux map along the center line above the burner for 50kW fire.

Utilizing the infrared camera, numerous cooling surface temperature data were collected along the center line with the spatial resolution of every 1cm. An overall infrared image of the heated wall after the burner was turned off is seen in Fig. 7. For each location, when the residual was found out to be 4 K the incident heat flux used for the simulation was determined to be the very heat flux at the location. By repeating this procedure along the center line, the heat flux mapping at the center line was obtained at every 1cm. Compared to the currently available methods for heat flux maps, *i.e.*, with 10kW/m^2 increments, the developed heat flux mapping method can provide more detailed heat flux maps(Fig. 8).

6. Conclusions

It is very important to understand the role of wall lining materials when they are exposed to a fire from an ignition source. Full − scale test methods permit an assessment of the performance of a wall lining material. However, fire growth predictions using models have been developed due to the costly expense associated with full − scale testing. The fire modeling requires the heat flux maps provided by the ignition burner flame as input data. Works to date were impeded by a lack of detailed characterization of the heat flux maps due to the use of limited instrumentation[6,7,11]. To increase the power of fire modeling, accurate and detailed heat flux maps from the ignition burner are essential.

The research was to develop a heat flux mapping procedure for a room test burner flame to a wall configuration utilizing surface temperature measurements from an infrared camera. High level spatial resolution for surface temperature was provided by an infrared camera, which is in contrast to "spot" resolution obtained from thermocouples or heat flux gauges.

As a part of heat flux mapping procedure one − dimensional heat conduction model was developed. The 1D temperature data from the model are compared with the 1D temperature data measured from the Cone Calorimeter tests[12]. The comparison allows the resolution of the model to be determined which is

±1kW/m^2. To validate the use of a 1D model to determine best estimate heat fluxes from a real fire situation, a commercial 3D conduction code, ALGOR's finite element analysis, was used for the purpose of comparison. It is acceptable to use the developed 1D heat conduction model in the area of the center line above the burner which showed 1D behavior through ALGOR runs.

A prototype experiment in a wall configuration was performed using the ISO 9705 test burner[1] to demonstrate the developed heat flux mapping procedure. Utilizing the infrared camera, numerous cooling surface temperature data were collected along the center line above the burner with the spatial resolution of every 1cm. Through the heat flux mapping procedure, the heat flux maps along the center line was obtained at every 1cm. Compared to the currently available methods for heat flux maps, *i.e.*, with lines of constant heat flux in 10kW/m^2 increments, the developed heat flux mapping method can provide more detailed heat flux maps.

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