NONFLAME SIMULATING EXPERIMENTAL METHOD FOR IGNITION PROCESS OF FIRE*

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ABSTRACT

Seven similarity numbers are given by this paper to describe the ignition process of combustible materials. Analysis points out that it is absolutely impossible to predict real process from small-scale simulating test in which the same material is used. Small-scale accurate simulating test should be done only by using different materials with the same similarity numbers. But if convective heat transfer and/or buoyancy force are negleted, it is also possible to use the same material in the small-sacle test by changing the scale of velosity V_0.

KEY WORDS: Fire science, Ignition process, Simulating test, Similarity number.

INTRODUCTION

Fire test is neccesary and important in scientific fire research, but up until now, people still use 1:1 scale test, or self simulation, in their tests to study fire.

Small-scale simulating test is prefered for research because of its advantages, suhc as less expenses, for simulating largy-scale fire. Unfortunately, the same combustible material is still used in the small-scale test nowadays, and it is obvious that people have enough reason to doubt the reliability of data gained from that test.

It is an urgent need to develop a fire simulating experimental method in order to find whether or not simulating test for fire exists except self simulation. This paper will try to answer this question for ignition process of fire.

DERIVATION OF THE CONSERVATION EQUATIONS

A control volume is selected at an ignition part of combustible material, with volume V, surrounding area A, physical value ϕ, and its density $\tilde{\rho}(=\phi/V)$. During an interval time $\delta\tau$, the variation of ϕ in volume V is

$$\Delta\phi=(\phi_{\tau+\delta\tau}-\phi_{\tau})+(\phi_{out}-\phi_{in}) \quad (1)$$

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The above equation is divided by the time interval $\delta\tau$, and by letting $\delta\tau \rightarrow 0$, we get

$$\frac{D\phi}{d\tau} = \frac{\partial\phi}{\partial\tau} + \int_A \tilde{\rho}(\vec{u} \cdot \vec{n})dA = \frac{\partial}{\partial\tau}\int_V \tilde{\rho}dV + \int_V \nabla \cdot (\tilde{\rho}\vec{u})dV$$

$$= \int_V [\frac{\partial\tilde{\rho}}{\partial\tau} + \nabla \cdot (\tilde{\rho}\vec{u})]dV \quad (2)$$

Equation (2) is the common for all following conservation equations.

1. Continuity equation

M, ρ are assumed as the mass and density of control volume respectively

$$\frac{DM}{d\tau} = \int_V [\frac{\partial\rho}{\partial\tau} + \nabla \cdot (\rho\vec{u})]dV$$

on the other hand, mass change of the control volume is caused by volatile escaping from combustible material when heated

$$-\frac{DM}{d\tau} = \int_A \rho m(\vec{D}_m \cdot \vec{n})dA = \int_V \nabla \cdot (\rho_m \vec{D}_m)dV$$

The continuity equation can be written

$$\frac{\partial\rho}{\partial\tau} + \nabla \cdot (\rho\vec{u}) + \nabla \cdot (\rho_m \vec{D}_m) = 0 \quad (3)$$

Equation (3) can be rewritten in the cartesian system

$$\frac{\partial\rho}{\partial\tau} + \frac{\partial(\rho u_i)}{\partial x_i} + \frac{\partial(\rho_m D_{mi})}{\partial x_i} = 0 \qquad i=1, 2, 3. \quad (4)$$

2, Momentum equation

ϕ, $\tilde{\rho}$ are now replaced by momentum $\vec{M}$, momentum density $\rho\vec{u}$ respectively in equation (2)

$$\frac{D\vec{M}}{d\tau} = \int_V [\frac{\partial(\rho\vec{u})}{\partial\tau} + \nabla \cdot (\rho\vec{u}\,\vec{u})]dV$$

the sum of all forces acts on the combustible material within the control volume must equal the change of the momentum per unit time. Those forces can be body forces $\vec{g}$ and surface forces $\vec{p}$

$$\frac{D\vec{M}}{d\tau} = \int_V \rho\vec{g}dV + \int_A (\vec{p} \cdot \vec{n})dA = \int_V [\rho\vec{g} + \nabla \cdot \vec{p}]dV$$

From above two formulas, the momentum equation can be obtained by adding the continuity equation

$$\rho\frac{D\vec{u}}{d\tau} = \rho\vec{g} + \nabla \cdot p + \vec{u} \cdot \nabla \cdot (\rho_m \vec{D}_m) \quad (5)$$

Stress $\vec{p}$ is expressed in following form

$$\vec{p}=-p-\frac{2}{3}\mu(\nabla\cdot\vec{u})\vec{I}+2\mu\vec{\epsilon}$$

Considering buoyancy force $\rho\beta\vec{g}\Delta T$, equation (5) can be rewritten in the cartesian system

$$\rho\frac{\partial u_i}{\partial\tau}+\rho u_i\frac{\partial u_i}{\partial x_j}=\rho g_i+\rho\beta g_i\Delta T-\frac{\partial p}{\partial x_i}-\frac{\partial}{\partial x_i}(\frac{2}{3}\mu\frac{\partial u_j}{\partial x_j})+\frac{\partial}{\partial x_j}(\mu\frac{\partial u_i}{\partial x_j})$$

$$+\frac{\partial}{\partial x_j}(\mu\frac{\partial u_j}{\partial x_i})+u_i[\frac{\partial}{\partial x_j}(\rho_m D_{m\,j})] \quad i, j=1, 2, 3. \tag{6}$$

3, Energy equation

ϵ, e are defined as total and internal energy per unit mass in control volume, $\epsilon=e+\frac{1}{2}u^2$. Total energy E and total energy density $\rho\epsilon$ are palced in the position of ϕ and $\tilde{\rho}$ respectively in equation (2)

$$\frac{DE}{d\tau}=\int_V[\frac{\partial(\rho\epsilon)}{\partial\tau}+\nabla\cdot(\rho\epsilon\,\vec{u})]dV$$

The causes which bring change of total energy are following

(a), Thermal heat transfer: $\frac{dQ}{d\tau}=\int_A(\vec{q}\cdot\vec{n})dA=\int_V\nabla\cdot\vec{q}dV=\int_V\nabla\cdot[\vec{q}_k+\vec{q}_h+\vec{q}_r]dV$

where, $\vec{q}_k=-k\nabla\cdot t$ as conductive heat flux in the combustible material;

$\vec{q}_h=-h(T-T_a)$ as convective heat flux at the surface of combustible material;

$\vec{q}_r=-\epsilon\sigma F(T^4-T_f^4)$ as radiative heat flux received by the combustible material.

(b), Work done by body forces: $\frac{dW_v}{d\tau}=\int_V(\vec{u}\cdot\rho\vec{g})dV$

(c), Work done by surface forces: $\frac{dW_a}{d\tau}=\int_A[\vec{u}\cdot(\vec{p}\cdot\vec{n})]dA=\int_V\nabla\cdot(\vec{u}\cdot\vec{p})dV$

We can get finally the energy equation using temperature form as following

$$\rho C_p\frac{DT}{d\tau}=\nabla\cdot[-k\nabla\cdot t]+\nabla\cdot[-h(T-T_a)]+\nabla\cdot[-\epsilon\sigma F(T^4-T_f^4)]$$

$$-p\nabla\cdot\vec{u}+\Phi+(C_pT-\frac{1}{2}u^2)\nabla\cdot(\rho_m\vec{D}_m) \tag{7}$$

$$\Phi=2\mu\vec{\epsilon}\nabla\cdot\vec{u}-\frac{2}{3}\mu(\nabla\cdot\vec{u})\vec{I}(\nabla\cdot\vec{u})$$

In the cartesian system, the energy equation (7) can be rewritten as following

$$\rho C_p\frac{\partial T}{\partial\tau}+\rho C_p u_i\frac{\partial T}{\partial x_j}=\frac{\partial}{\partial x_i}(-k\frac{\partial t}{\partial x_i})+\frac{\partial}{\partial x_i}[-h(T-T_a)]+\frac{\partial}{\partial x_i}[-\epsilon\sigma F(T^4-T_f^4)]$$

$$-p\frac{\partial u_i}{\partial x_i}+\tilde{\Phi}+(C_pT-\frac{1}{2}u_i^2)\frac{\partial}{\partial x_j}(\rho_m D_{m\,j}) \quad i, j=1, 2, 3. \tag{8}$$

where, $\tilde{\Phi}=\mu(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i})^2+\frac{4}{3}\mu[(\frac{\partial u_i}{\partial x_i})^2-(\frac{\partial u_i}{\partial x_i})(\frac{\partial u_i}{\partial x_j})]$ i=1, 2, 3; j=i+1, j=1(i=3)

DIMENSIONAL ANALYSIS OF IGNITION PROCESS

As a first step in the dimensional analysis, dimensionless quantities are written following

$$\bar{x}_i=\frac{x_i}{L};\quad \bar{p}=\frac{p}{\rho_0 V_0^2};\quad \bar{g}_i=\frac{g_i}{V_0^2/L};\quad \bar{\phi}_i=\frac{\phi_i}{\phi_0},\ \phi=(\rho,\rho_m,D_m,\tau,u,C_p,k,h,\beta,\epsilon,\sigma,\mu,t);$$

$$\Delta\bar{T}=\frac{\Delta T}{\Delta T_0},\ \Delta T=T-T_a,\ \Delta T_0=T_w-T_a;\quad \Delta\bar{N}=\frac{\Delta N}{\Delta N_0},\ \Delta N=T^4-T_f^4,\quad \Delta N_0=T_w^4-T_f^4.$$

Introducing the dimensionless quantities into the continuity, momentum, and energy equations respectively, results in

(a), Continuity equation (4)

$$[\frac{L}{V_0\tau_0}]\frac{\partial\bar{\rho}}{\partial\bar{\tau}}+\frac{\partial(\bar{\rho}\bar{u}_i)}{\partial\bar{x}_i}+\frac{\partial(\bar{\rho}_m\bar{D}_{m_i})}{\partial\bar{x}_i}=0\qquad i=1,2,3.\tag{9}$$

(b), Momentum equation (6)

$$[\frac{L}{V_0\tau_0}]\bar{\rho}\frac{\partial\bar{u}_i}{\partial\bar{\tau}}+\bar{\rho}\bar{u}_i\frac{\partial\bar{u}_i}{\partial\bar{x}_j}=\bar{\rho}\bar{g}_i+[\frac{\beta_0 g_0\Delta T_0 L^3}{\nu_0^2}][\frac{\mu_0}{\rho_0 V_0 L}]^2\bar{\rho}\bar{\beta}\bar{g}_i\Delta\bar{T}$$
$$-\frac{\partial\bar{p}}{\partial\bar{x}_i}-[\frac{\mu_0}{\rho_0 V_0 L}]\frac{\partial}{\partial\bar{x}_i}(\frac{2}{3}\bar{\mu}\frac{\partial\bar{u}_j}{\partial\bar{x}_j})+[\frac{\mu_0}{\rho_0 V_0 L}]\frac{\partial}{\partial\bar{x}_j}(\bar{\mu}\frac{\partial\bar{u}_i}{\partial\bar{x}_j})$$
$$+[\frac{\mu_0}{\rho_0 V_0 L}]\frac{\partial}{\partial\bar{x}_j}(\bar{\mu}\frac{\partial\bar{u}_j}{\partial\bar{x}_i})+\bar{u}_i[\frac{\partial}{\partial\bar{x}_j}(\bar{\rho}_m\bar{D}_{m_j})]\qquad i,j=1,2,3.\tag{10}$$

(c), Energy equation (8)

$$[\frac{L}{V_0\tau_0}]\bar{\rho}\bar{C}_p\frac{\partial\bar{T}}{\partial\bar{\tau}}+\bar{\rho}\bar{C}_p\bar{u}_i\frac{\partial\bar{T}}{\partial\bar{x}_j}=[\frac{k_0}{\mu_0 C_{p0}}][\frac{\mu_0}{\rho_0 V_0 L}]\frac{\partial}{\partial\bar{x}_i}(-\bar{k}\frac{\partial\bar{t}}{\partial\bar{x}_i})$$
$$+[\frac{h_0}{\rho_0 C_{p0} V_0}]\frac{\partial}{\partial\bar{x}_i}(-\bar{h}\Delta\bar{T})+[\frac{\epsilon_0\sigma_0\Delta N_0}{h_0\Delta T_0}][\frac{h_0}{\rho_0 C_{p0} V_0}]\frac{\partial}{\partial\bar{x}_i}(-\bar{\epsilon}\bar{\sigma}F\Delta\bar{N})$$
$$-[\frac{V_0^2}{C_{p0}\Delta T_0}]\bar{p}\frac{\partial\bar{u}_i}{\partial\bar{x}_i}+[\frac{V_0^2}{C_{p0}\Delta T_0}][\frac{\mu_0}{\rho_0 V_0 L}]\bar{\Phi}+\bar{C}_p\bar{T}(\bar{\rho}_m\bar{D}_{m_j})$$
$$-[\frac{V_0^2}{C_{p0}\Delta T_0}]\frac{1}{2}\bar{u}_i^2\frac{\partial}{\partial\bar{x}_j}(\bar{\rho}_m\bar{D}_{m_j})\qquad i,j=1,2,3.\tag{11}$$

where, $\bar{\Phi}=\bar{\mu}(\frac{\partial\bar{u}_i}{\partial\bar{x}_j}+\frac{\partial\bar{u}_j}{\partial\bar{x}_i})^2+\frac{4}{3}\bar{\mu}[(\frac{\partial\bar{u}_i}{\partial\bar{x}_i})^2-(\frac{\partial\bar{u}_i}{\partial\bar{x}_i})(\frac{\partial\bar{u}_i}{\partial\bar{x}_j})]$ i=1, 2, 3; j=i+1, j=1(i=3)

The equations (9), (10), (11) are also used to describe the similar physical phenomenon as the equations (4), (6), (8), so the similarity coefficients in above equations must equal 1, or the following seven similarity numbers have the same values in both orginal and simulating models.

(a) Universal time number: $H=\frac{L}{V\tau}$;

(b) Reynolds number: $Re=\frac{\rho VL}{\mu}$;

(c) Grashof number: $Gr=\frac{\beta g\Delta TL^3}{\nu^2}$;

(d) Eckert number: $Ec=\frac{V^2}{C_p\Delta T}$;

(e) Prandtl number: $Pr=\frac{\mu C_p}{k}$;

(f) Stanton number: $St=\frac{h}{\rho C_p V}$;

(g) Radition-convection number: $Rc=\frac{\epsilon\sigma\Delta N}{h\Delta T}=\frac{\epsilon\sigma\Delta NL}{k\Delta T}$.

where, $(\nu=\frac{\mu}{\rho})$.

SIMULATING CONDITIONS FOR IGNITION PROCESS

It is obvious that both original and simulating tests are all done in the Globe gravitational accelarational field, and σ is Stefan-Boltzmann constant, so we have $g_0=1$ and $\sigma_0=1$, as a result

$$(a)\ H_0=\frac{L}{V_0\tau_0}=1;\quad (b)\ Re_0=\frac{\rho_0 V_0 L}{\mu_0}=1;\quad (c)\ Gr_0=\frac{\beta_0\Delta T_0 L^3}{\nu_0^2}=1;\quad (d)\ Ec_0=\frac{V_0^2}{C_{p0}\Delta T_0}=1;$$

$$(e)\ Pr_0=\frac{\mu_0 C_{p0}}{k_0}=1;\quad (f)\ St_0=\frac{h_0}{\rho_0 C_{p0} V_0}=1;\quad (g)\ Rc_0=\frac{\epsilon_0\Delta N_0}{h_0\Delta T_0}=\frac{\epsilon_0\Delta N_0 L}{k_0\Delta T_0}=1.$$

Following simulating conditions are derived from above similarity numbers

$$\epsilon_0\Delta N_0=\frac{k_0}{C_{p0}L}\left(\frac{\mu_0}{\rho_0 L}\right)^2;\quad \Delta T_0=\frac{1}{C_{p0}}\left(\frac{\mu_0}{\rho_0 L}\right)^2;\quad \tau_0=L\left(\frac{\rho_0 L}{\mu_0}\right);$$

$$L=\frac{C_{p0}}{\beta_0}=\frac{k_0}{h_0}=\frac{k_0}{\rho_0 C_{p0} V_0}. \tag{12}$$

If the same material is still used in the simulating test, we have

$$\epsilon_0=k_0=\beta_0=h_0=\mu_0=\rho_0=C_{p0}=1$$

and final result must be

$$L=1,\ \Delta N_0=1,\ \Delta T_0=1,\ \tau_0=1$$

That is self simulation.

If different material is selected and used in the simulating test, equation (12) would offer the possibility for simulating the ignition process of fire. When $\Delta N_0<1$ is chosen, a thermal resource could be used in the test instead of real fire. That is called as the nonflame simulating experimental method.

It is also noticed that the possibility for simulation exists in the simulating test by changing scale of velosity V_0 while using the same material when the buoyancy force and/or convective heat transfer can be negleted.

CONCLUSION

Small-scale simulating fire test is useful and important in fire research because of its less expenses, more convenient for repetition and more possible to simulate largy-scale fire.

This paper has derived seven similarity numbers which must be obeyed in simulating test for studing the ignition process of combustible material.

According to these similarity numbers, following conclusions are gained

(a) Fire simulating tests can possibly be done by using the different materials;

(b) Changing the velosity scale would offer approximate simulating test even using the same material in which the buoyancy force and/or convective heat transfer can be negleted;

(c) Real flame could be replaced by thermal resource which has lower temperature in such simulating tests.

NOMENCLATURE

A area, (m^2)	C_p specific heat of material, (J/kgK)
D_m escaping velosity of volatile, (m/s)	F shape factor of radiation
$\vec{g}$ body force per unit mass, (m/s^2)	g gravitational accelaration, (m/s^2)
h heat transfer coefficient, (J/m^2K)	k thermal conductivety, (J/mK)
L length, (m)	$\vec{M}$ momentum, (N)
M mass, (kg)	$\vec{n}$ normal unit vector
$\vec{p}$ stress, (N/m^2)	p normal stress, (N/m^2)
$\vec{q}$ heat flux per unit area, (W/m^2)	T,t temperature, (K)
$\vec{u}$ velosity vector, (m/s)	V volume, (m^3)
β thermal expansion coefficient, (K^{-1})	ϵ emissivity of material
$\vec{\varepsilon}$ shape changing stress, (s^{-1})	ρ density, (kg/m^3)
μ dynamic viscosity, (kg/ms)	σ Stefan-Boltzmann constant
τ time, (s).	

Footnote

a air	f flame	m volatile
w wall surface	out flow out	in flow in

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