The Occurrence and Mechanisms of Fire Whirls

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Motivation

Increasing Urbanization →

Expanding Boundaries of Urban Residential Areas to Reach Pure Wildland →

Creating a New Type of Fire:

Conflagrations at the Urban-Wildland Interface

(mechanisms comparatively poorly understood) →

There is need to develop effective means of fire prevention and fire suppression to inhibit fire spread through urban-wildland boundaries.

This requires better understanding of types of fires.

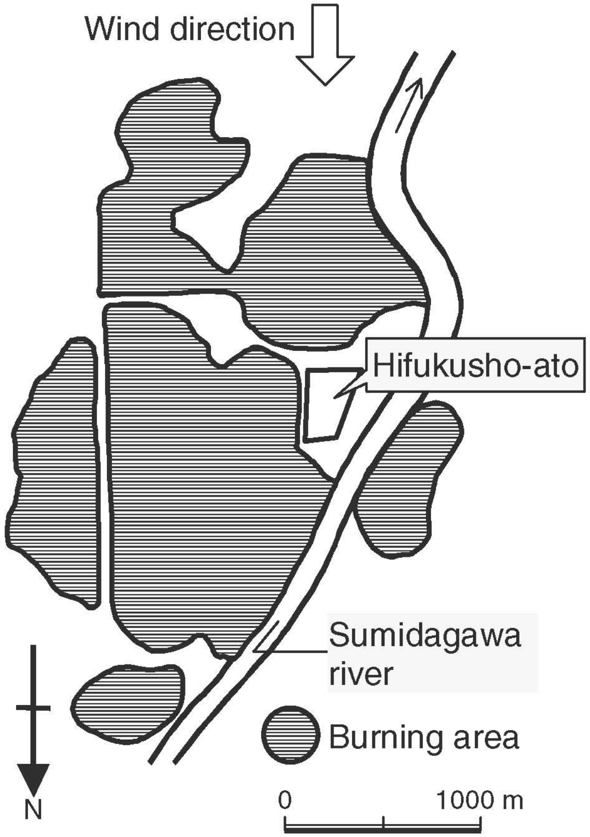
The Importance of Fire Whirls at the Urban-Wildland Interface

- Fire whirls can occur during both urban and wildland fires.
- When they occur, flame spread rates can be increased by enhanced flame radiation and increased convective heat transfer, both known to be associated with fire whirls.
- In addition, fire whirls have stronger plumes that lead to spotting, that is, creating new fires at a distance by fire brands which are lofted up into the air, carried by the wind, and land while burning.

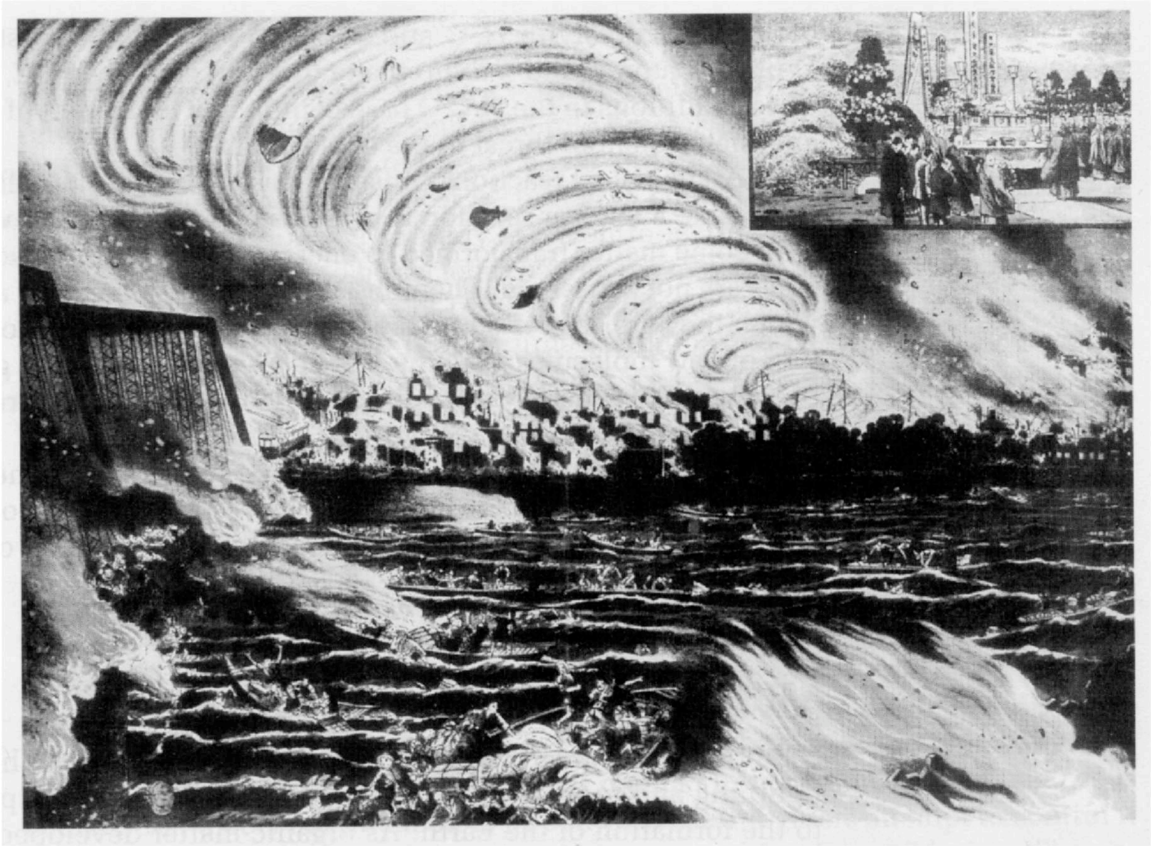
Death in the Great Kanto Earthquake

- Noon, Sept. 1, 1923, Kanto area magnitude 7.9 earthquake strikes downtown Tokyo.
- Stoves cooking lunch set houses on fire.
- 40,000 people evacuate to 70,000 m^2 open Hifukusho-ato area to escape fires.
- Wind is from south at 4 to 5 m/s.
- Gigantic fire whirls sweep the open area.
- 38,000 people die from burns.

Diagram (a) and Painting (b) of the Hifukusho-ato Fire-Whirl Area During the Great Kanto Earthquake and Fire, Sept. 1, 1923



a)



b)

Diagram of Types of Fire Whirls

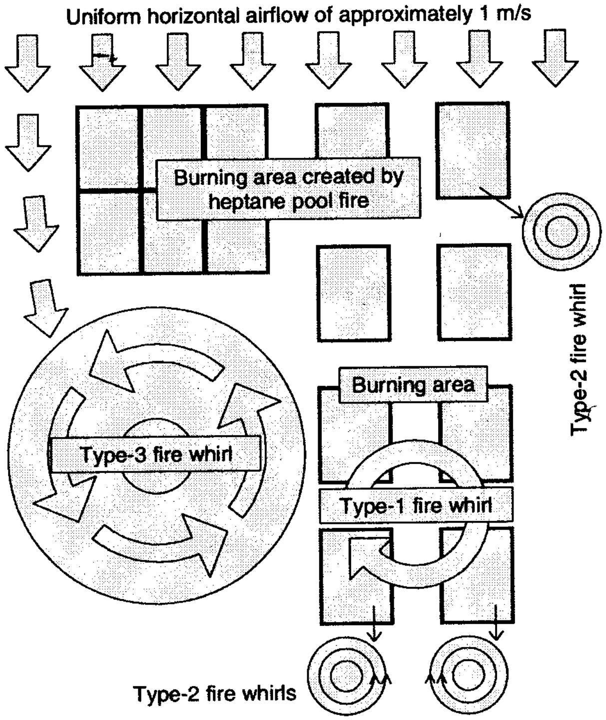


Fig. 2 Schematic of the 1/1000th scale-model experiment conducted at BRI and of the five different fire whirls that were observed.

K. Kuwana, K. Sekimoto, K. Saito, F.A. Williams, Y. Hayashi, and H. Masuda, ***AIAA Journal,*** vol. **45**: 16-19 (2007).

Classification of Fire Whirls

- Type 1: Steady and centered over burning area. (This type was studied carefully by Emmons & Ying, *Proc Combust Inst.* 11, 475, 1966.)
- Type 2: Steady or transient downwind of burning area. (This type is often seen in wildland fires, e.g. Brown & Davis, *Forest Fire: Control and Use*, McGraw-Hill, 1973.)
- Type 3: Steady or transient and centered over an open area adjacent to an asymmetric burning area with wind. (This could be most severe.)

Focus of the Presentation

- Controlling Mechanisms/Relevant Parameters
- Estimation of Flame Heights in Fires
- Structures of Type 1 Fire Whirls
- Application of a Burgers Vortex Model
- Structures of Type 3 Fire Whirls
- Unknown Aspects of Fire Whirls
- Future Research Needs

Relevant Parameters

- Momentum-Controlled Jets:

  Reynolds Number $Re=Ud/\nu$

- Buoyancy-Controlled Plumes:

  Froude Number $Fr=U^2/(gdr)$

- Rotation-Controlled Fire Whirls:

  Rossby Number $Ro=U/(\Omega d)$

Expect momentum control (Re important) at large Fr, buoyancy control (Re unimportant) at small Fr, but rotation may control if Ro is small enough. [Roper: Re scaling at small Fr for BS.]

Flow-Geometry Approximations

- CONICAL, Expanding in Downstream Axial Direction
  - Turbulent Momentum-Controlled Jet
    - (Tollmien, 1926)
  - Turbulent Vertical Buoyant Plume (Boussinesq)
    - (Morton, Taylor and Turner, 1956)
  - Turbulent Vertical Buoyant Gaseous Fuel Jets
    - (Putnam and Speich, 1963)
  - Vertical Rotating-Screen Fire Whirl (Boussinesq)
    - (Emmons and Ying, 1967)
- CYLINDRICAL; Axial Right Circular Cylinder
  - Flames of Large Fires (Thomas, 1963)
  - Vortices (e.g. Burgers, 1948)

Flame Lengths, L (1)

When buoyancy-controlled, L depends on Fr and

r = density difference/air density

α= entrainment coefficient, i.e., radial inflow velocity/axial velocity (≈0.1)

f = stoichiometric fuel-air ratio (<0.2) and for a general fuel

$C_mH_nO_o$+[m+(n/4)-(o/2)(O_2+4N_2)]➔

$m$$CO_2$+($n$/2)$H_2O$+(4$m$+$n-2o$)$N_2$

f = (12m+n+16o)/[144(m+n/4-o/2)]

Air entrainment controls L because f is small.

Flame Lengths, L (2)

Conical Geometry:

$$(\pi/4)d_f^2\rho_f u_f = f(\pi\alpha L^2)\rho_a \alpha u_s,$$

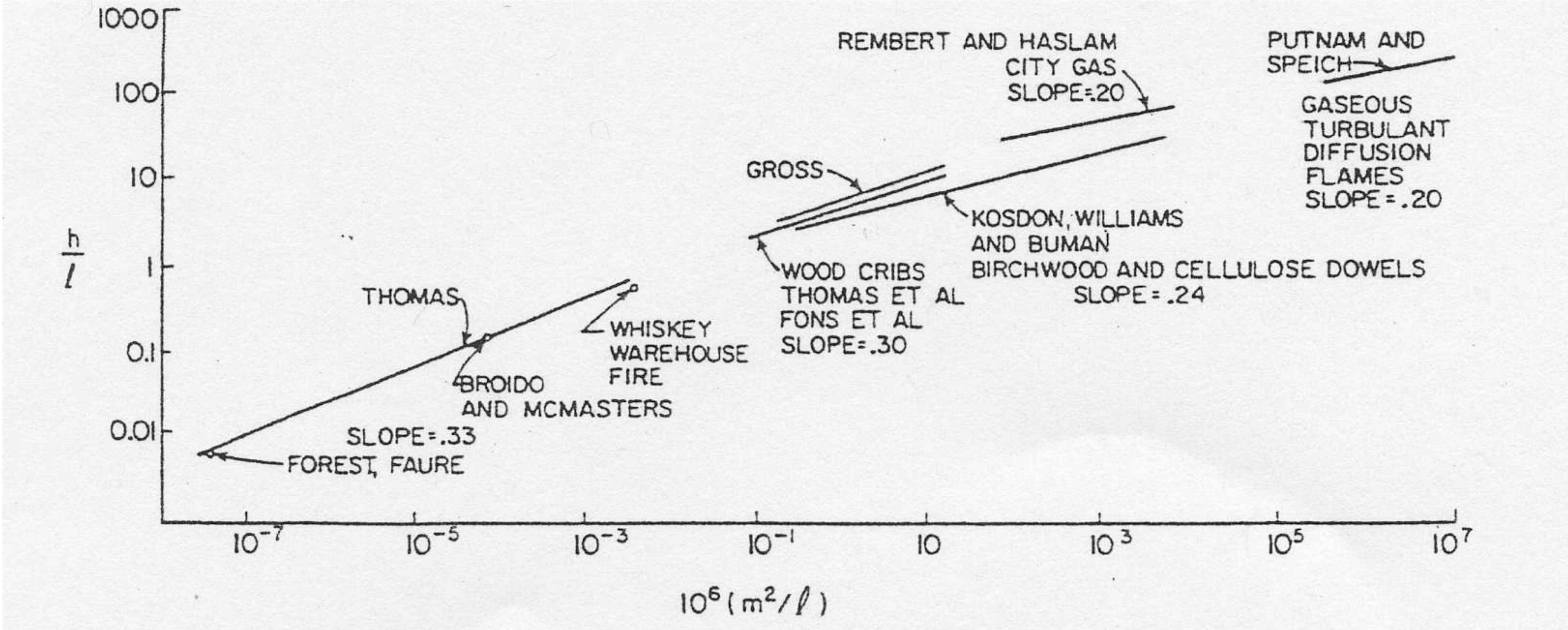
with $u_s=(Lgr)^{1/2}$, $u_f=U$, $d_f=d$, get $L/d \approx (Fr)^{1/5}$

Cylindrical Geometry:

$$(\pi/4)d_f^2\rho_f u_f = \mathrm{f}(\pi d_f L)\rho_a \alpha u_s$$

with same replacements, get $L/d \approx (Fr)^{1/3}$

Measured Flame Heights Versus Froude Number (m in g/cm^2s; l in cm)



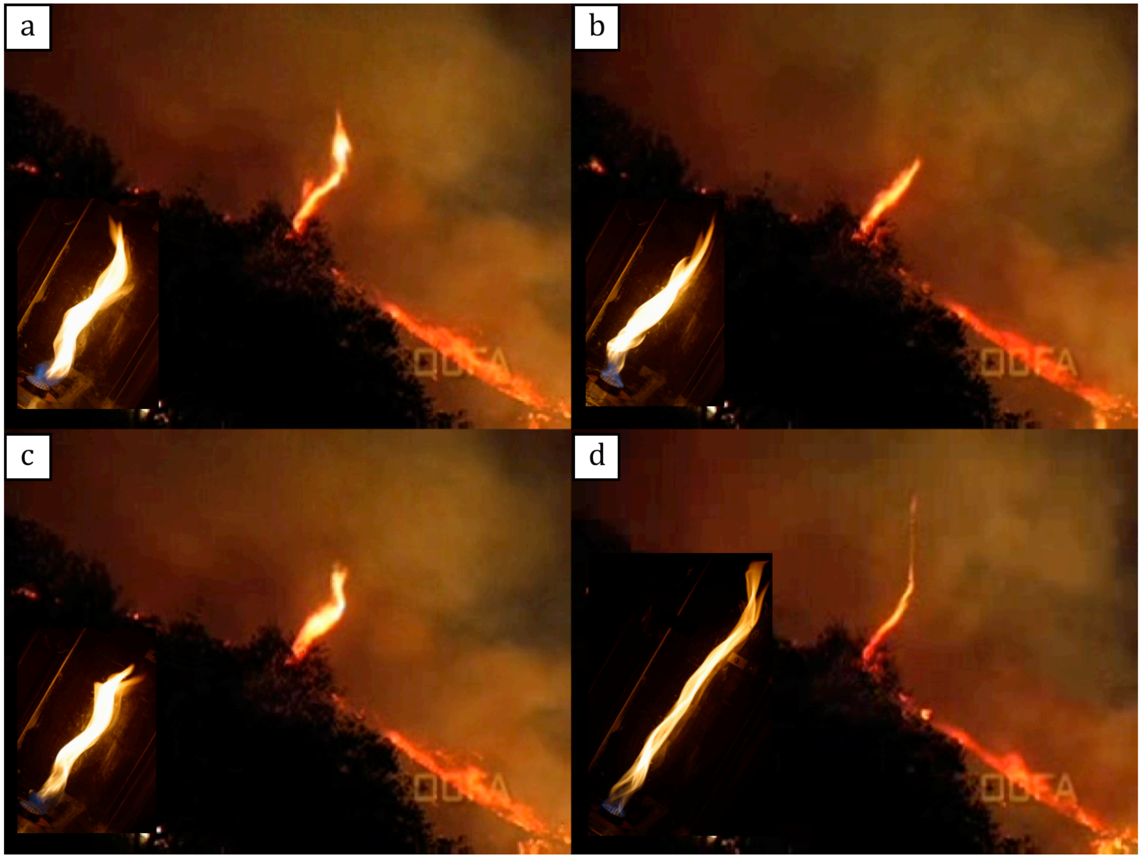
Large-Fire Flame Height, H

- Entrainment velocity, v, is generally proportional to upward velocity, $(gz\Delta\rho/\rho)^{1/2}$, (z=height).
- Total air entrainment rate is proportional to $zd\rho v=0.1dz^{3/2}\rho(g\Delta\rho/\rho)^{1/2}$.
- Total fuel mass flow rate is proportional to md^2.
- Equating flame height to height at which fuel-air ratio is stoichiometric gives $20md^2/4=0.1\ dH^{3/2}\rho(g\Delta\rho/\rho)^{1/2}$.
- Hence $H\approx[50md/(g\rho\Delta\rho)^{1/2}]^{2/3}$, i.e., n=1/3.

Structures of Type 1 Fire Whirls

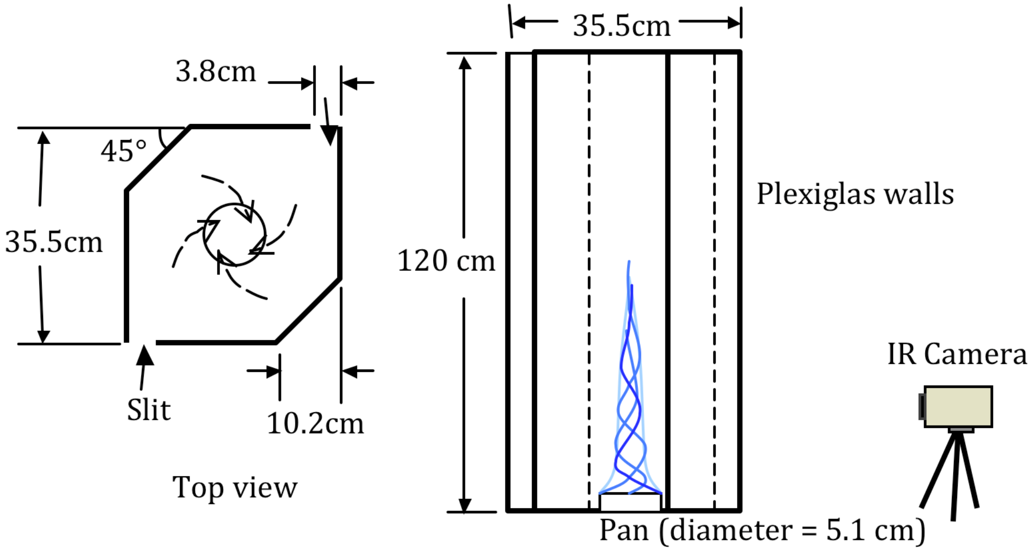
- Generally expected vertical, buoyancy-control.
- But a 30m straight one inclined at 30° was seen in 2007 fire in Southern California.
- A 1/30 scale model was constructed in the laboratory successfully, appearing identical.
- Inclination suggests rotation control (Ro).
- Similarity in structure to vertical whirls implies that if strong enough (Ro<Fr) they, too, may be rotation-controlled.

Inclined Fire Whirls

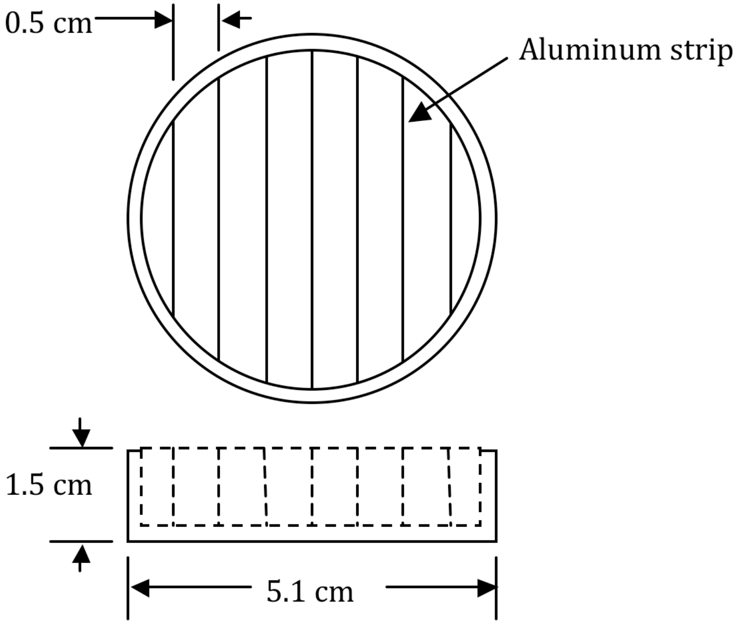


Field photo with scale model inset in lower left-hand corner.

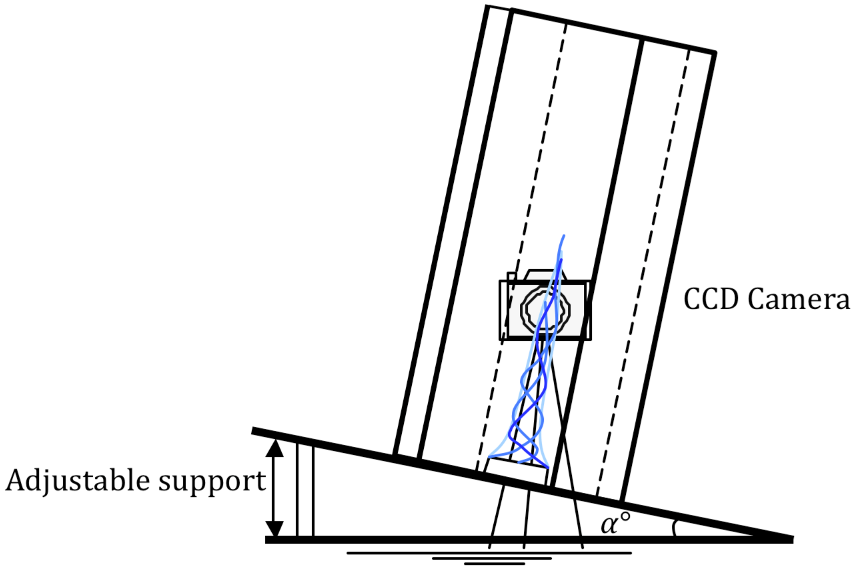
Scale-Model Experiment



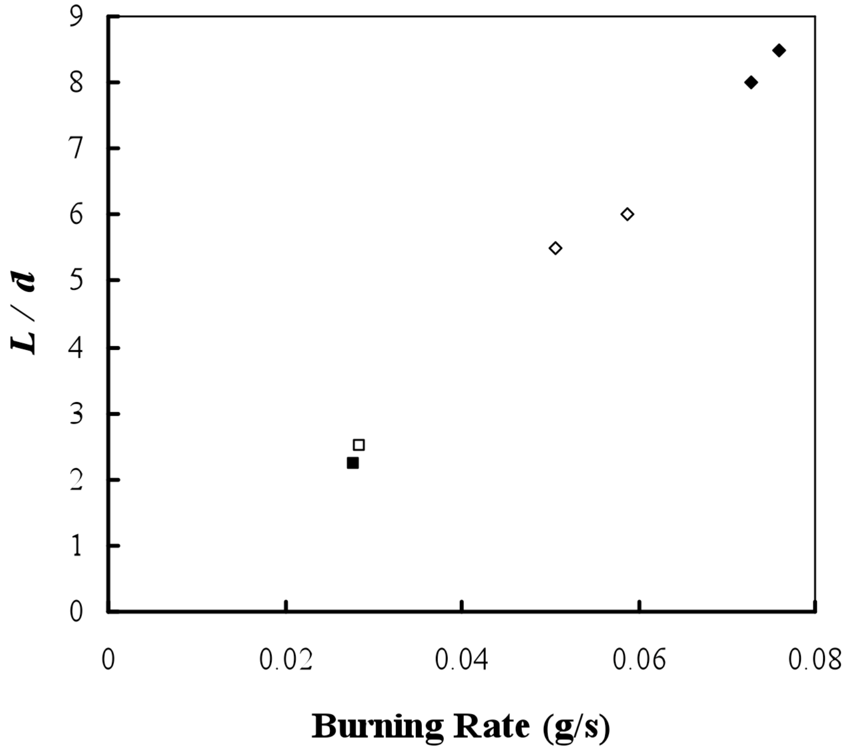
Slotted-Pan Design



Inclined-Firewhirl Apparatus

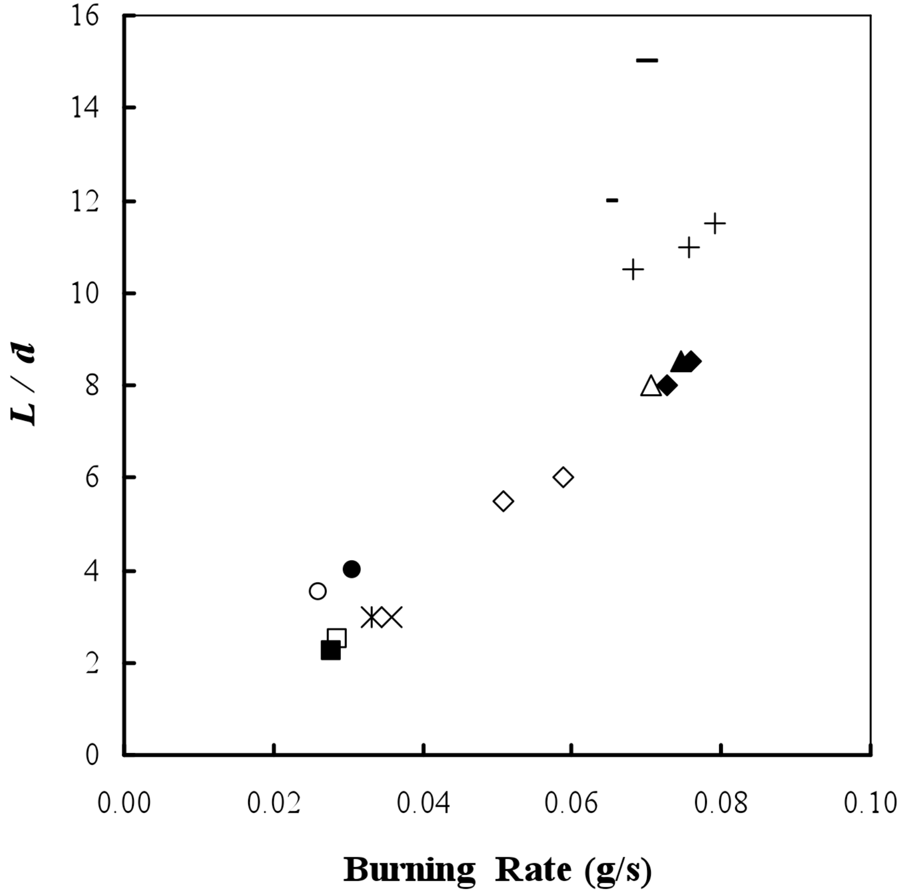


Methanol Measurements



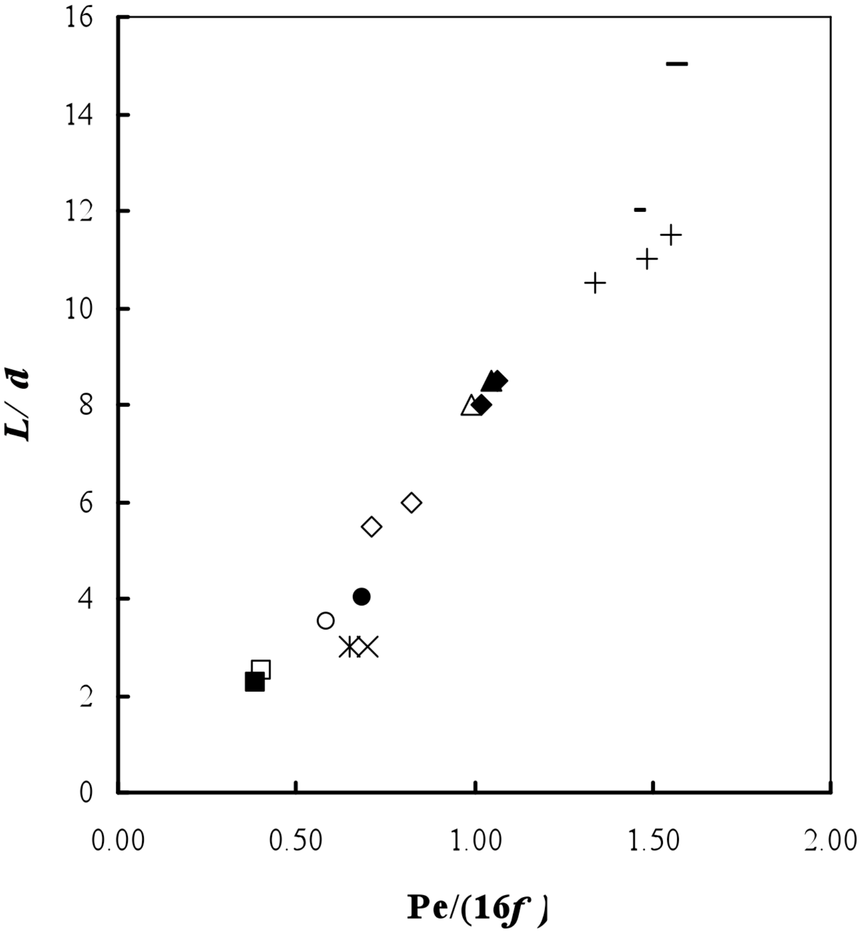
Vertical orientation; open symbols ordinary pan; solid symbols slotted pan; squares without whirl apparatus; diamonds with fixed frame.

All Alcohol Measurements



At a given burning rate flame length increases in going from methanol to ethanol to propanol.

Correlation of Flame Lengths



VALUES OF f

Methanol: 0.155

Ethanol: 0.111

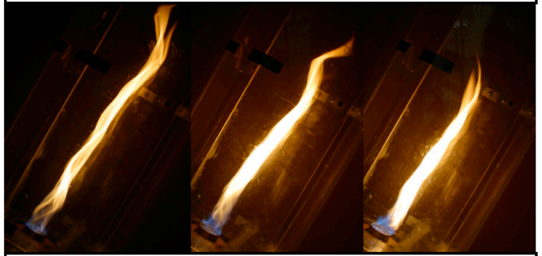
Propanol: 0.097

Burke-Schumann theory correlates but under-predicts L by a factor of 10.

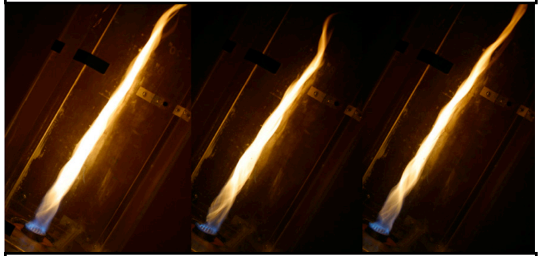
Effect of Blocking the Slot

28cm

33cm



38cm



51cm

Longer slots produce longer flames.

Burgers Vortex Model

$$u = u_{\mathrm{f}} + 4\nu s / a^2 , \qquad \text{(A1)}$$

$$v = -2\nu r / a^2 , \qquad \text{(A2)}$$

and

$$w = (b/r)[1 - e^{-(r^2/a^2)}], \qquad \text{(A3)}$$

in which s and r are the axial and radial coordinates, respectively, a is the constant core radius ($4\nu/a^2$ being the constant axial strain rate), and $2\pi b$ is a constant that measures the circulation far outside the core

$d_f u_s = (2a)(4\nu L/a^2)$, $\alpha = a/(2L)$, turbulent diffusivity: ν ➔ $\Gamma c = 2\pi bc$.

$L/d = (\rho_f/\rho_a)(Ud)/(16cf\Gamma)$,

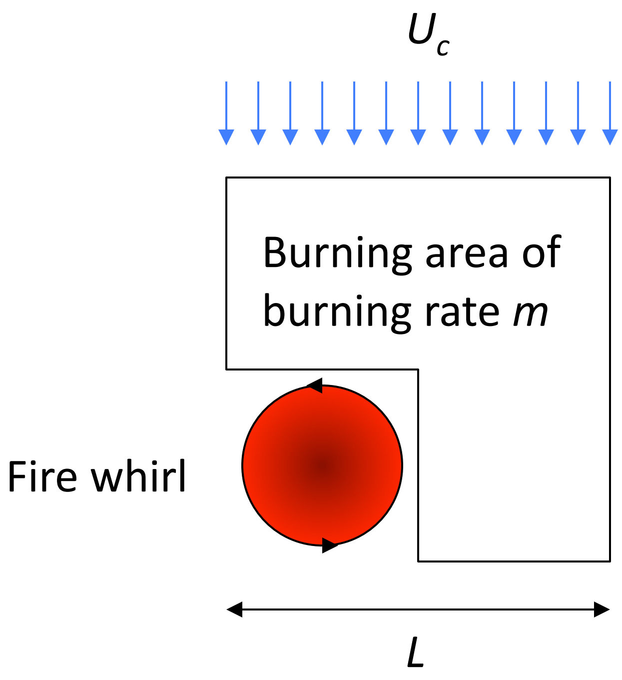
$L/d \approx Ro$, Rossby- number scaling; BAD.

Correction factor $\exp[(\rho_a/\rho_s - 1)^{1/2}(\Gamma/D)]$?

Axial pressure gradient $-\rho_a(16s\nu^2/a^4)$ accelerates the light core.

Burning rate: $u_f = [(2\nu/a^2)BDLe]^{1/2}$, νD ➔ Γc, could be OK.

Illustration of Type 3 Fire Whirl



Type 3 fire whirls are generated when the burning area's fire and plume obstruct the lateral wind, preventing flow across the burning area and creating a circulation region for fuel and air entrainment.

From scale-model experimental results and overall balance equations, an estimate for scaling of the critical wind velocity for generating the most severe whirls can be obtained as follows:

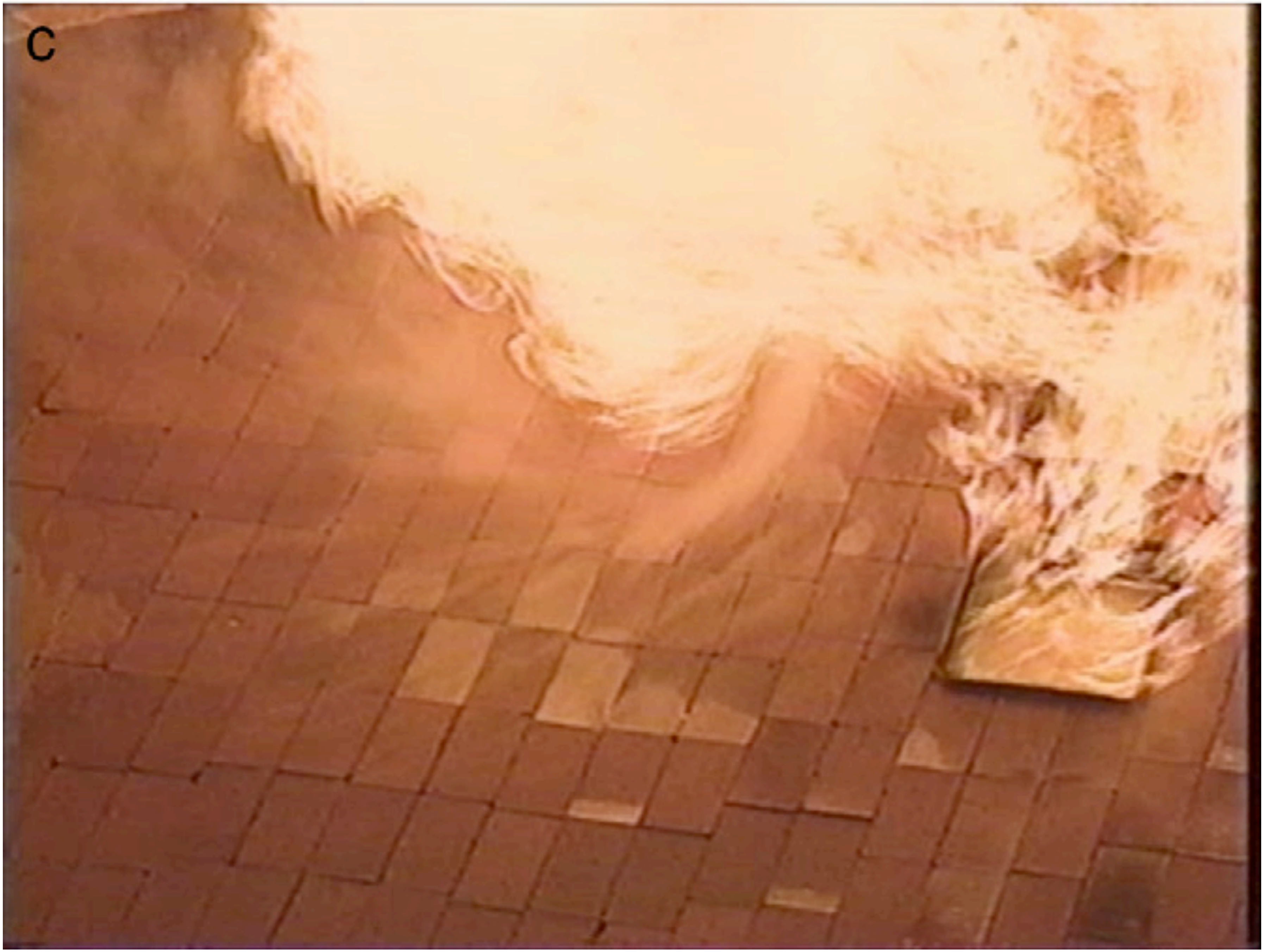
$$U_c \sim L^{3/8} m^{1/4}$$

Scale Modeling of Type 3 Fire Whirls

- 1/100th scale field experiment: Soma & Saito, *Combustion and Flame*, 86, 269, 1991.
- 1/1000th scale wind-tunnel experiments: Hayashi, Ohmiya &Saga, *Int. J. Fire Science and Technology*, 22, 17, 2003.
- 1/2500th scale laboratory experiment: Saito (Kozo), personal communication, 2006.

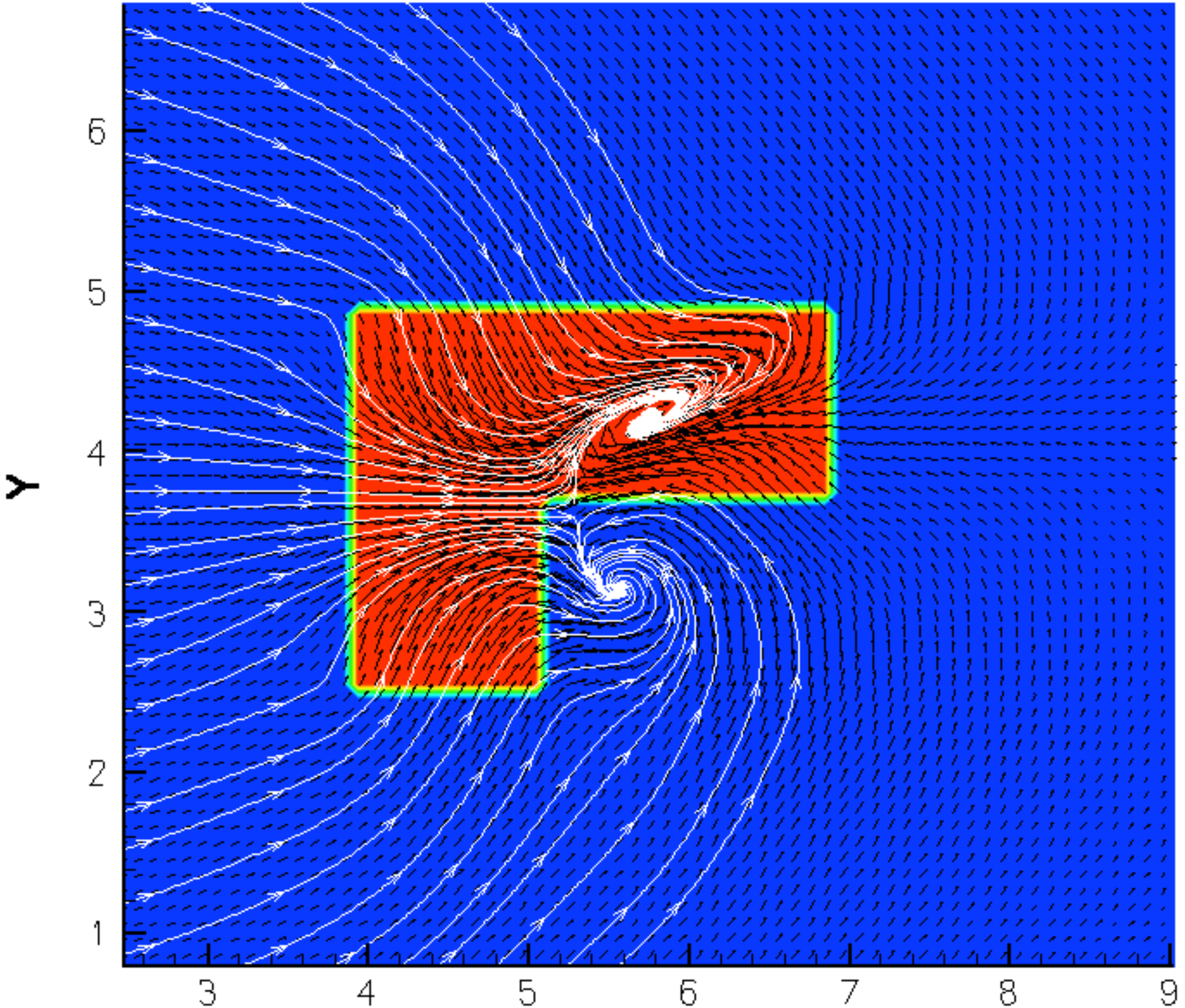
Experiment at 1/1000th Scale

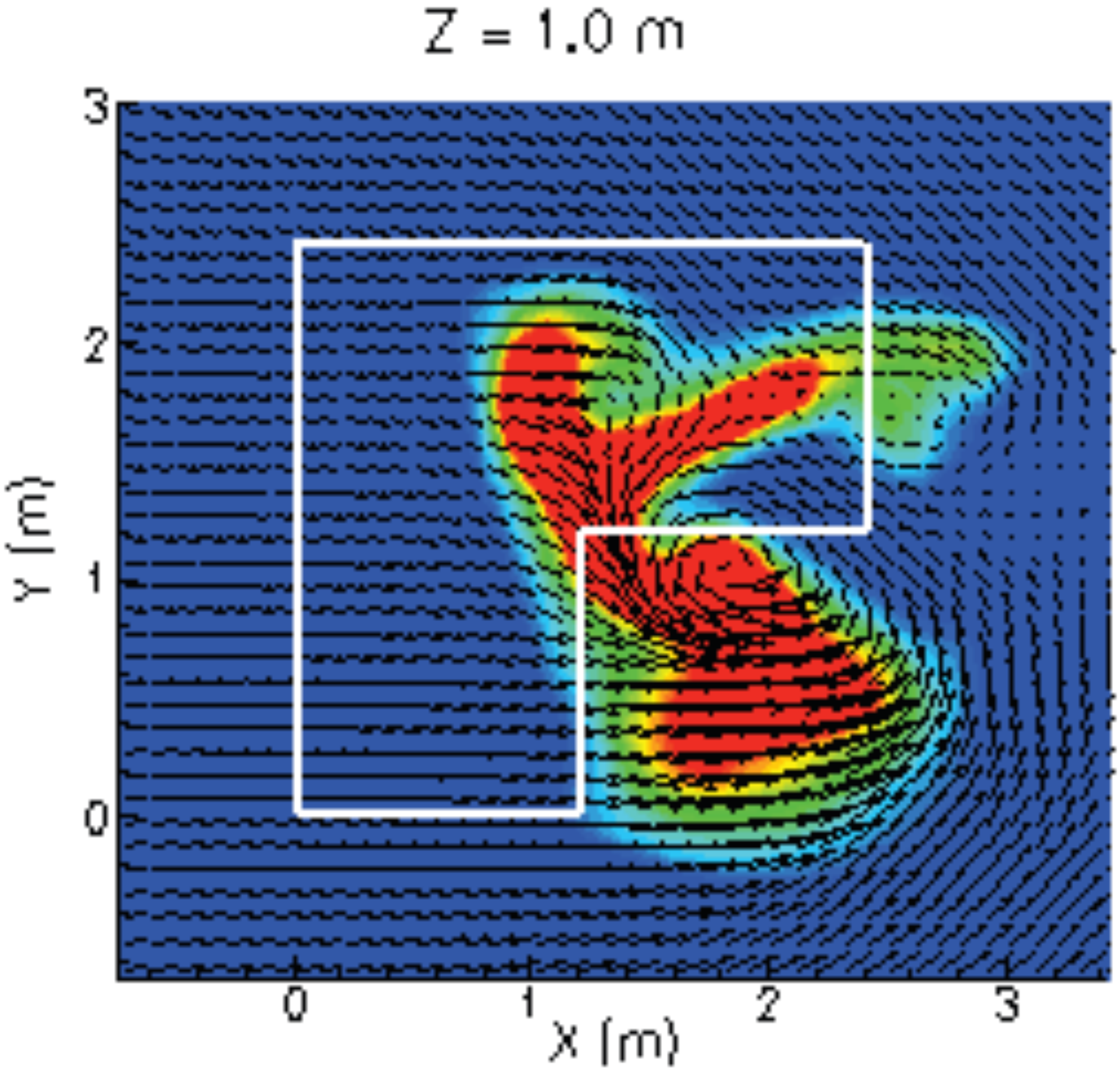
- Building Research Institute, Tsukuba, Japan
- 14 rectangular pans, 0.3m by 0.4m, n-heptane fuel, ignited simultaneously, wind velocity 0.5 m/s to 2.0 m/s, burning duration 2 min.
- Weak whirls at 0.5 m/s; fire plumes strongly tilted downstream at 2.0 m/s; intense type 3 fire whirls at 1.0 m/s.
- Photograph of the latter in the following slide.

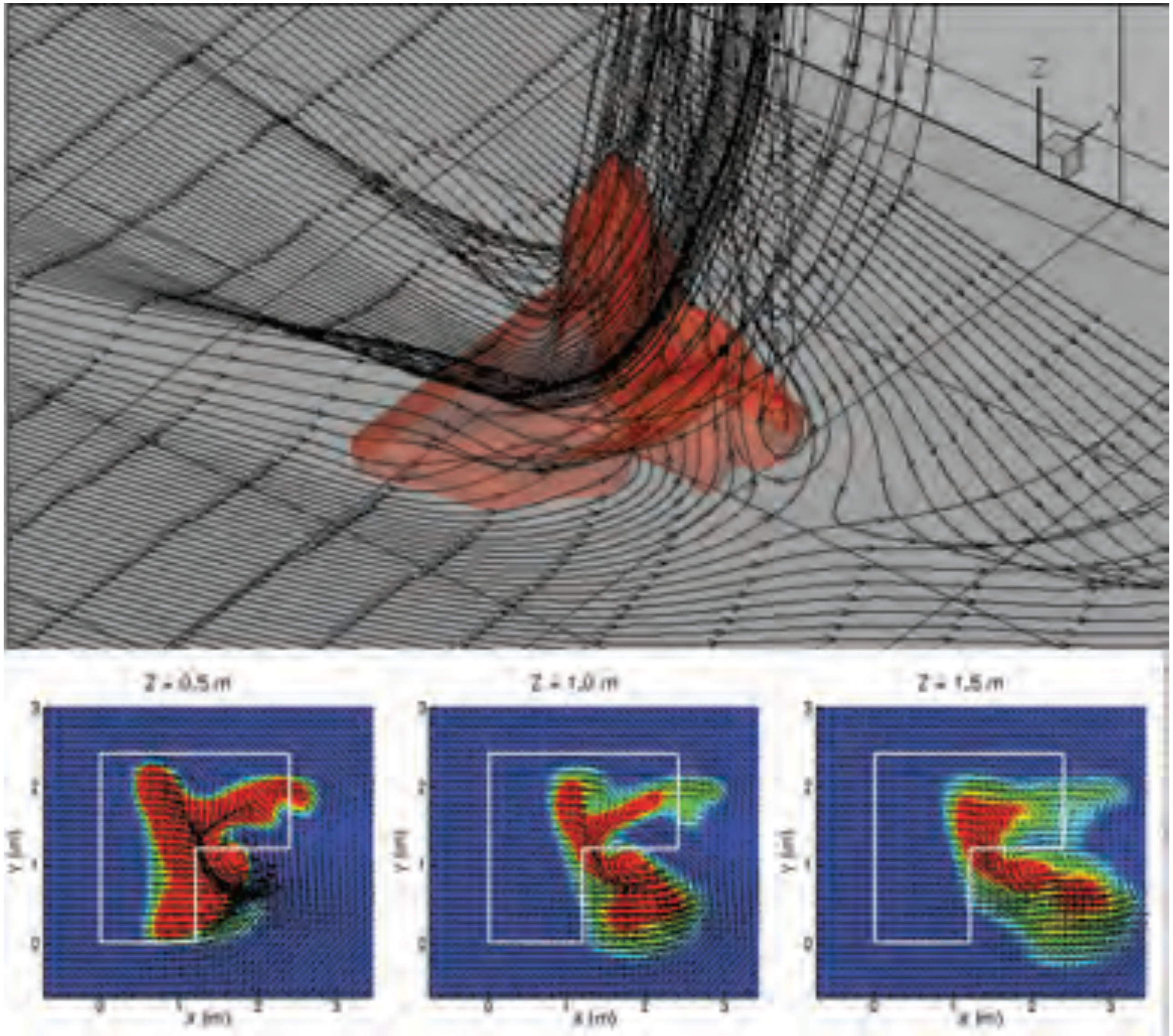

c

Computation of Type 3 Fire Whirls

- Roughly 1/1000th scale: Junhui Liu & Elaine Oran, personal communication, 2007/2008. Length, L, 2.4 m, fire simulated by energy release rate, q, of 125 to 2000 kW/m^2, wind velocity, U, 0.25 to 1.5 m/s.
- Results similar to experiments even though not fully resolved (i.e. LES).
- Preceding scaling law, with U_c=4 m/s for Kanto, gives U_c=0.7 m/s for q=500 kW/m^2; computations show most intense whirl at 0.5 m/s for this case, which is close.


Y
6
5
4
3
2
1
3
4
5
6
7
8
9


Z = 1.0 m
3
2
1
0
Y (m)
0
1
2
3
X (m)


Z
Y
Z = 0.5 m
Z = 1.0 m
Z = 1.5 m
Y (m)
X (m)
0
1
2
3

Analysis of Type 3 Fire Whirls

- The fire plume is an obstacle to the wind.
- Circulation UL is generated by interaction.
- Increasing U bends the plume leeward.
- Vortex strength is a maximum for U about 1/3 of the jet vertical velocity (AIAA J., 1988).
- The value of the wind velocity U_c for the most intense fire whirls thus is proportional to the upward gas velocity in the fire plume.

Scaling for Type 3 Fire Whirls

- Upward velocity in buoyancy-controlled fire plumes is proportional to $(gH)^{1/2}$. (H=flame height, g=acceleration of gravity)
- H/L is proportional to F^n, $1/5 \leq n \leq 1/3$. (Froude number $F=m^2/(\rho^2 gL)$, ρ=gas density, m=mass burning rate per unit area; m varies as q)
- Hence the wind velocity, U_c, for the most intense fire whirls, varies as $L^{1/2}(q^2/L)^{n/2}$.
- For n=1/4, get $L^{3/8}m^{1/4}$, the cited scaling.

Test Against Scale-Model Experiments

Is U proportional to $L^{3/8}m^{1/4}$ for maximum strength? Use the experimental measurements of m and U_c.

Kanto: $m=1$ (selected value) Estimated $U_c=4.0$ m/s

1/100: $m=2$ Calc. $U_c=0.9$ m/s Meas. $U_c=1.3$ m/s

1/1000: $m=100$ Calc. $U_c=1.0$ m/s Meas. $U_c=1.0$ m/s

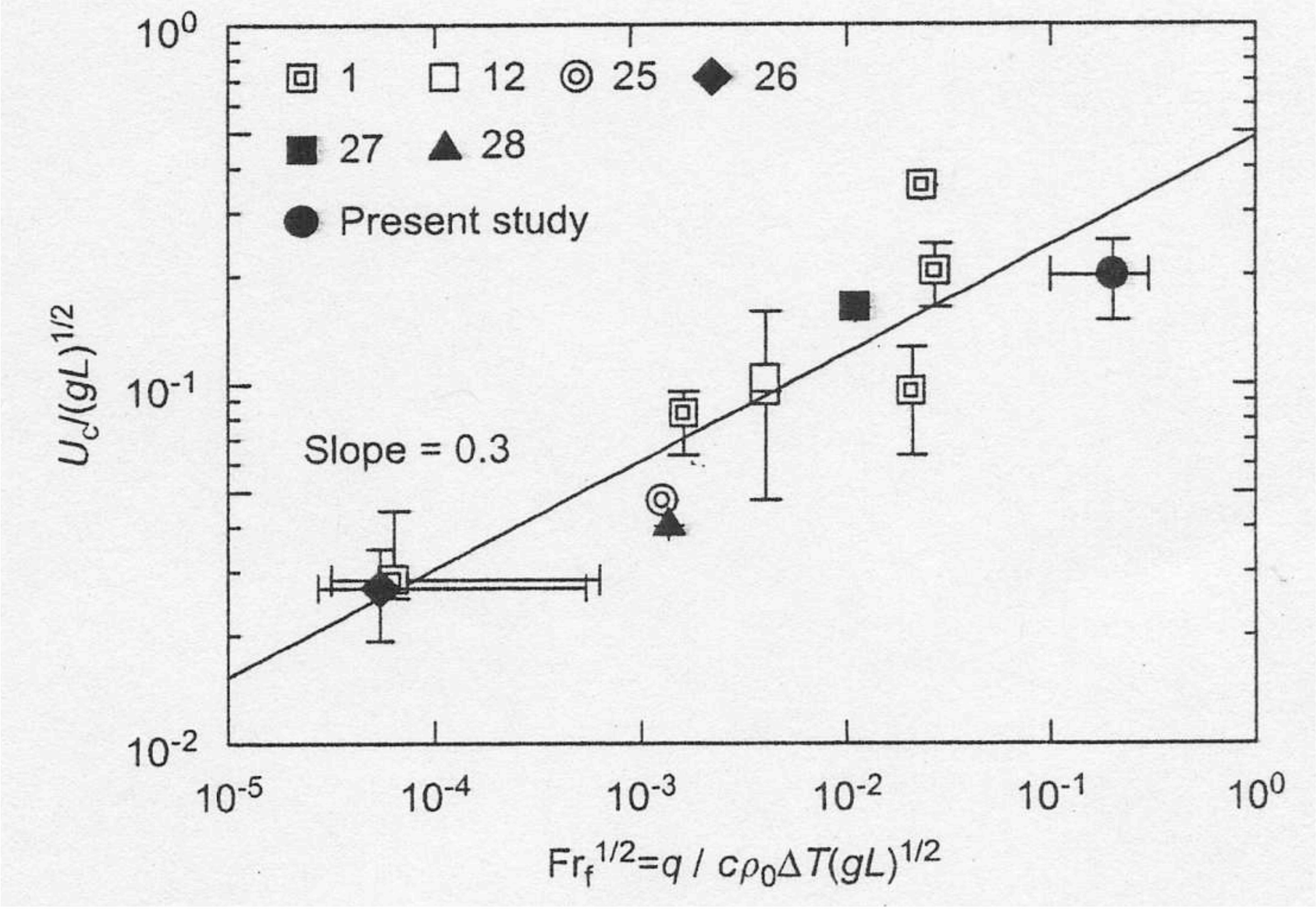
1/2500: $m=10$ Calc. $U_c= 0.4$ m/s Meas. $U_c=0.3$ m/s

Doesn’t look bad.

Alternative Scaling for Most Intense Type 3 Fire Whirls

- For $n=1/3$, U_c is proportional to $(mL)^{1/3}$, i.e. $(qL)^{1/3}$.
- Prediction can be tested in a non-dimensional plot of $U_c/(gL)^{1/2}$ versus √ Froude number, defined as $q/[c\rho_0 \Delta T(gL)^{1/2}]$, ($c$=air specific heat, ρ_0= air density, ΔT= flame temperature minus ambient).
- Kuwana, Sekimoto, Saito & Williams, Fire Safety J. 2008, using data from (1, 12) scaling, (25) tornadoes (Nature,1962), (26) Hamburg fire storm (1945, published 1963), (27) urban fire simulation (Proc. Combust. Inst., 1974), (28) 1GW fire (1990).

Test of Scaling for Most Intense Fire Whirls



Conclusions

- The theory for flame-height scaling appears to be in reasonable agreement with experiment.
- Strong fire whirls of type 1 are rotation-controlled and need Rossby-number scaling.
- The wind velocity needed for type 3 fire whirls to be most severe is approximately proportional to the cube root of the product of the horizontal length and the mass burning rate per unit area.

Unknown Aspects of Fire Whirls

- Time-dependent mechanism of development of type 3 fire whirls. (Experimentally they occur late and are preceded by type 1 and/or 2 fire whirls.)
- Optimum configurations for development of most severe fire whirls. (Are there geometries that can produce whirls more severe than type 3?)
- Detailed mechanisms by which fire whirls enhance burning rates and increase spotting.
- Variable-density effects on flame lengths of strong fire whirls of type 1.

Research Needs for Fire Whirls

- Physically reasonable simplified model for fire-whirl structure predicting burning-rate enhancement.
- Variable-density Burgers-vortex model for predicting flame lengths of type 1 fire whirls.
- Scaling laws for the time to onset of type 3 fire whirls and for their duration.
- Fire-whirl experiments in different configurations.
- Better-resolved computational fire-whirl modeling.
- Improved determination of fire-whirl types and prevalence at the urban-wildland interface.

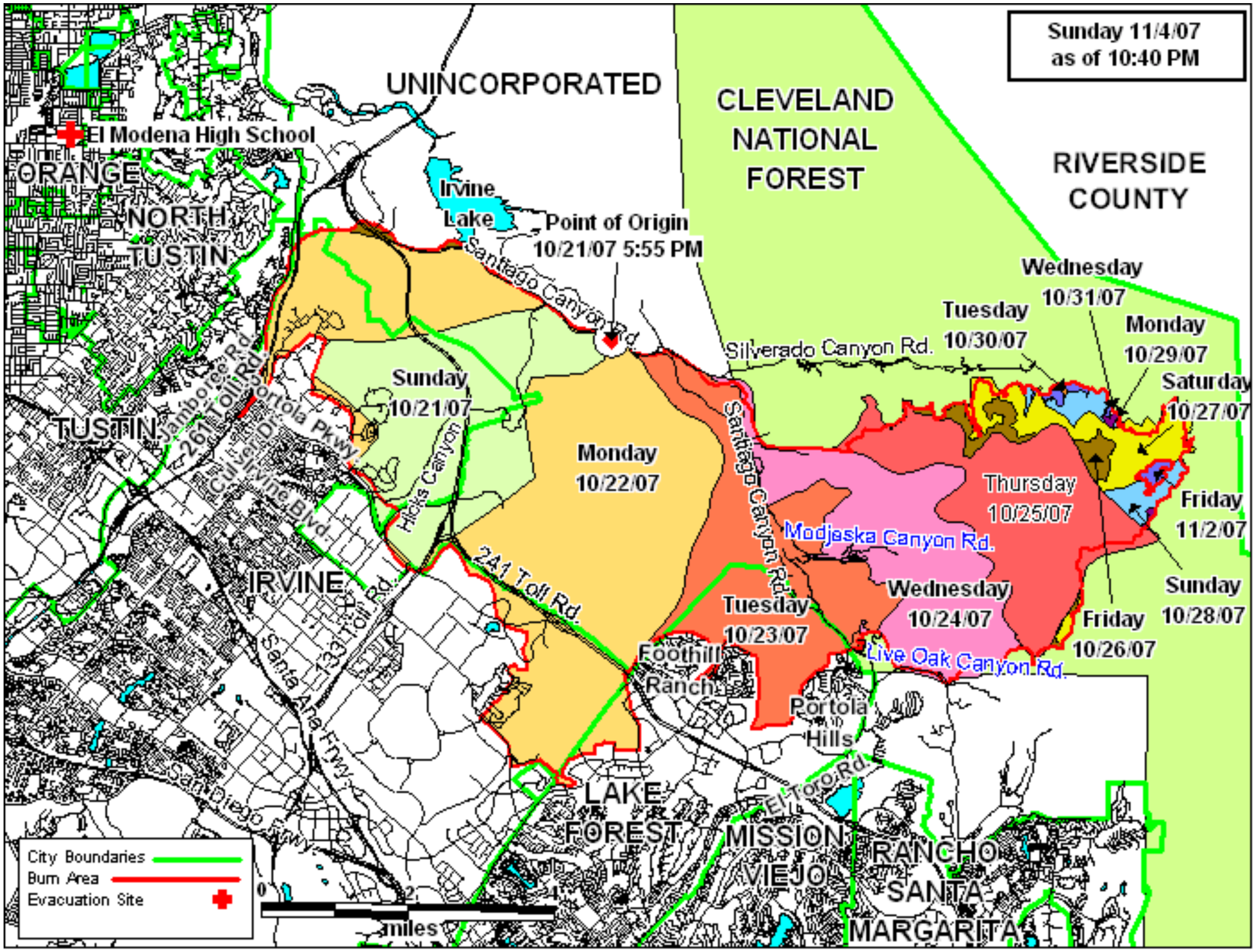
Thank You

Santiago Fire (Oct 21st – Nov 8th, 2007)*

- **INCIDENT#:** ORC 07068555
- **FIREFIGHTING ASSETS (at the peak of the fire):**
  - 1,982 Fire Personnel
  - 212 Engines/Trucks
  - 1 Lead Plane
  - 9 Helicopters
  - 1 Air Attack Plane (with relief)
  - 4 Fixed-wing Air Tankers
  - 25 Handcrews
  - 17 Dozers
  - 13 Water Tenders
- **INJURIES:** Sixteen minor injuries to fire personnel
- **ACRES BURNED:** 28,517
- **STRUCTURES BURNED:**
  - Eight residential structures were damaged and fourteen destroyed.
  - Three outbuildings were damaged and twenty-four destroyed.
  - Three commercial buildings were damaged and four destroyed.

*Ref: Orange County Fire Authority (OCFA), http://www.ocfa.org/

Strong fire whirls reported on Oct 24, ’07.



*Map from Orange County Fire Authority (OCFA), http://www.ocfa.org/

Computed Location of Center of Whirl (Downwind Distance Xc)