UKCTRF ANNUAL MEETING
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Large Eddy Simulations of the Formation of Fire Whirls

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WarwickFIRE

SCHOOL OF ENGINEERING
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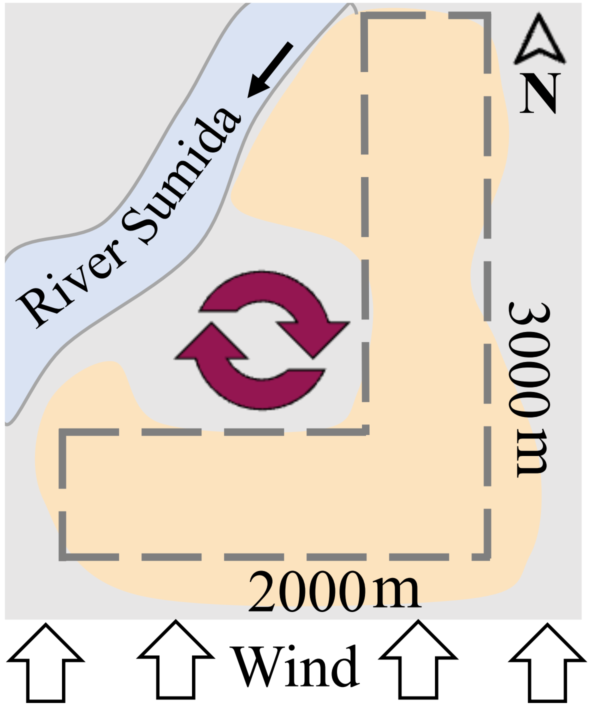
Hifukusho-ato Fire Whirl (HAFW)

September 1, 1923, Kanto, Japan

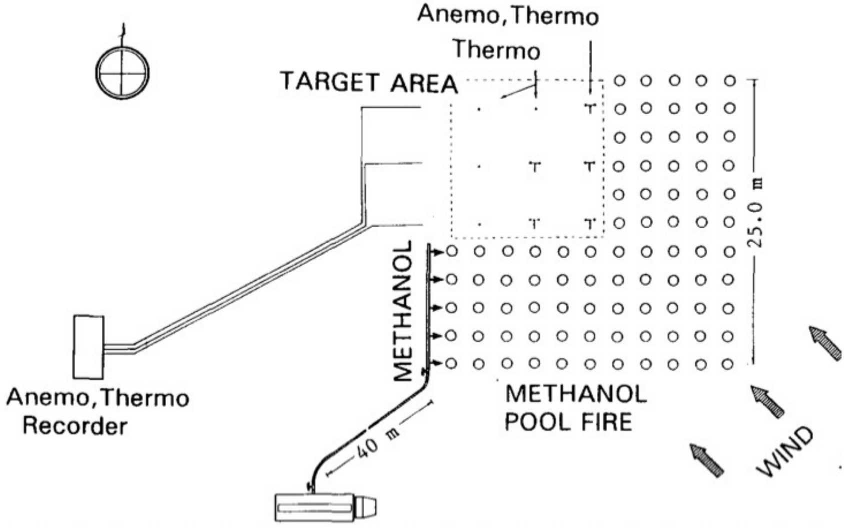
Memorial painting of the HAFW[1]



Schematic view of the prototype HAFW[2]

[1]M. Shikamachi, The Great Kanto Earthquake and the Era of Reconstruction, Shikamachi Museum, Tokyo, Japan, 2012
[2]S. Soma, K. Saito, Combust. Flame 86 (1991) 269–284.

Experimental Efforts



Experimental setup of the large scale outdoor fire[1]

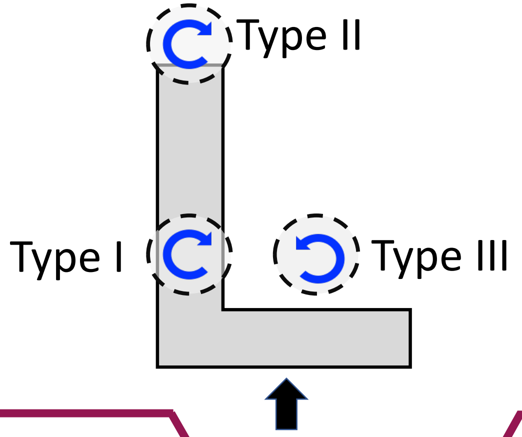
scale-model experiment[2,3]

Crosswind velocity is a key element in the generation of fire whirls

Type I : the stationary fire whirls over the fire source

Type II : periodically shedding off from the fire source

Type III : formed over the open area downstream of the L-shape fire



[1]S. Soma, K. Saito, Combust. Flame 86 (1991) 269–284.
[2]Kuwana et al., Fire Safety Journal 43 (2008) 252–257
[3]Kuwana et al., Aerospace Letters, AIAA Journal. 45(1) 2007.

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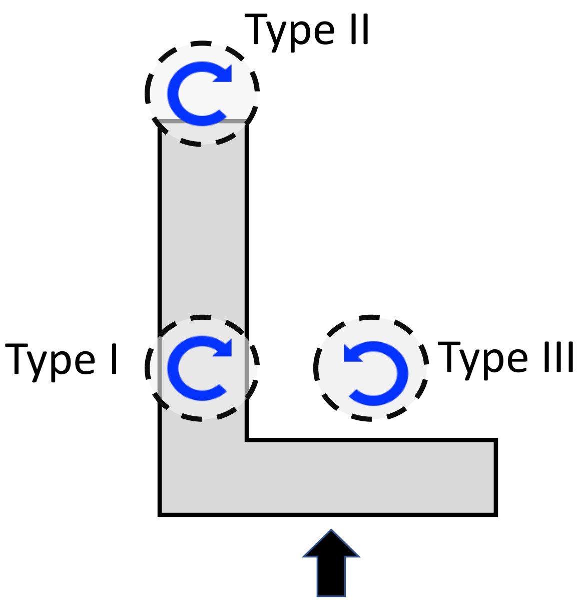
Motivation

Fire whirls remain poorly understood.

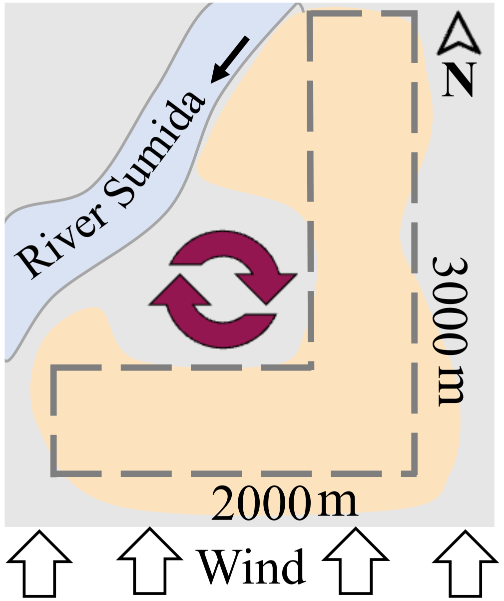
- Difficulties in obtaining quantitative data in experiments
- Numerical studies are not available in the literature



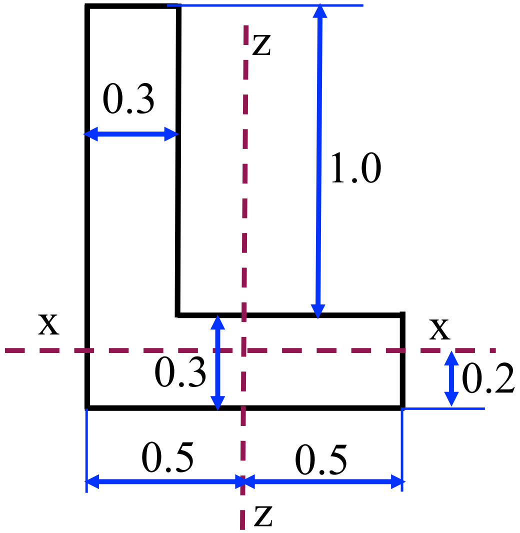
- Prediction of fire whirls over the L-shaped fire source in a crossflow
- Investigation of the structure of fire whirl
- Studying the formation mechanism of fire whirls

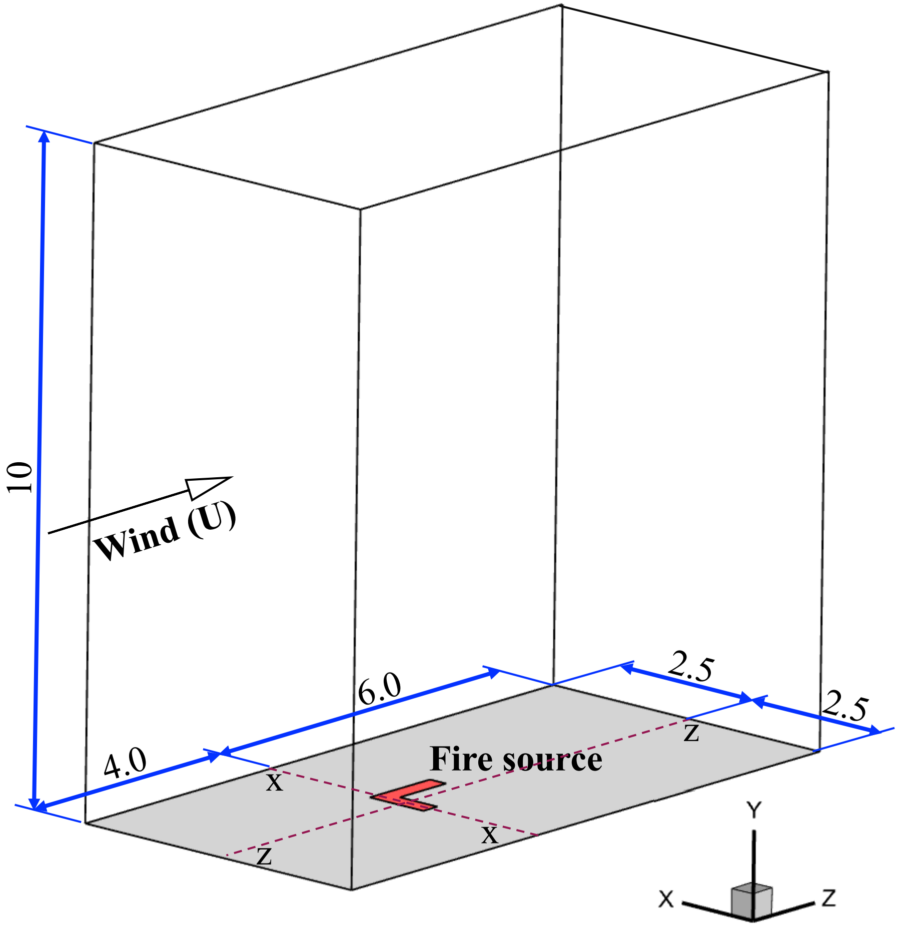
Computational Domain

Computational code : OpenFOAM 8.0



L-Shape fire source





Numerical Setup

- Numerical models: in-house version of *fireFoam solver*

  Combustion: Eddy Dissipation Concept (EDC) with Infinitely fast chemistry[1]

  Turbulence closure: One equation eddy-viscosity LES model

  Soot Model: Improved partially stirred reactor (PaSR) based soot model[2]

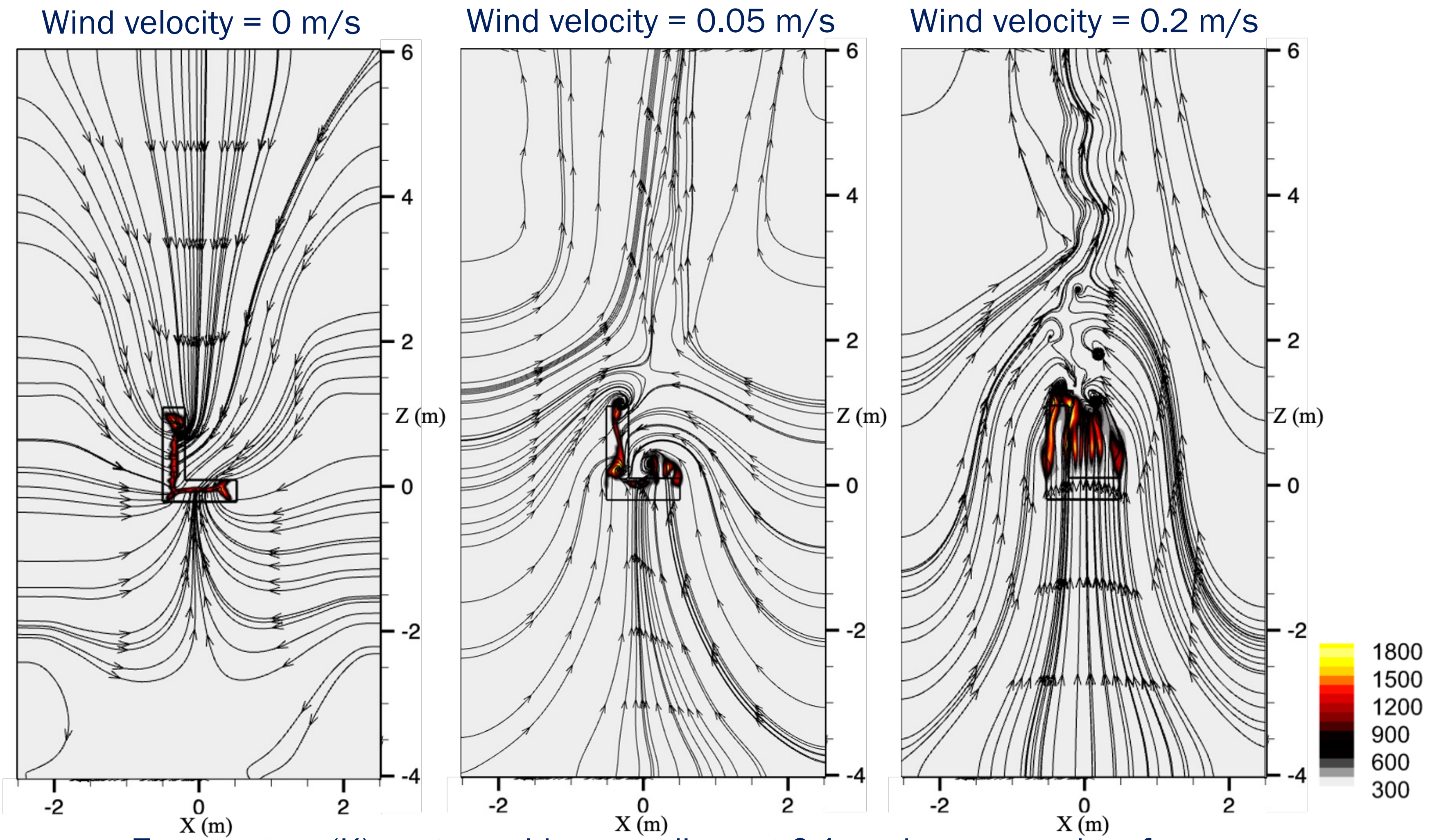
  Radiation heat transfer: P-1 radiation model

- Fire source: Heptane pool fire (115 kW heat release rate)

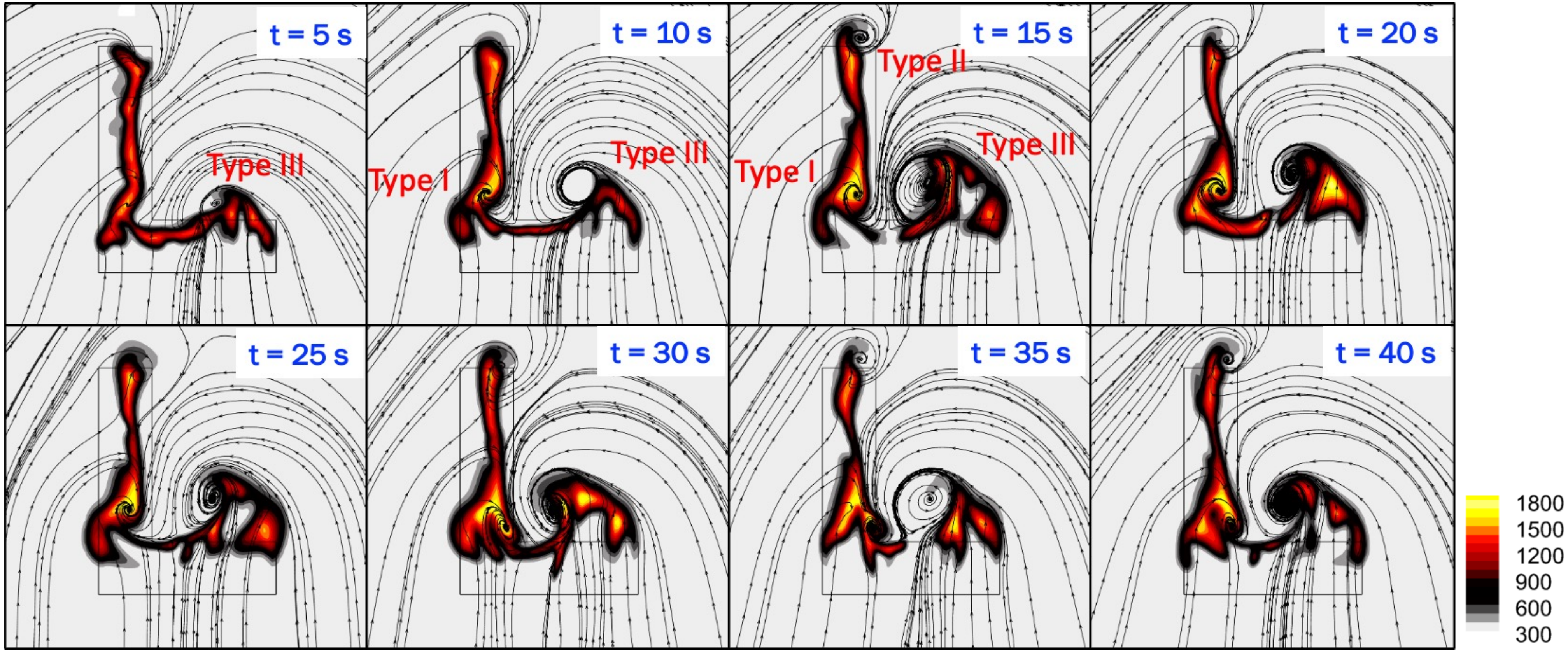
- Computational Grid: 6 Million cells $\left(D^* = \dot{Q} \Big/ \left(\rho_0 c_{p_0} T_0 \sqrt{g} \right); \ D^*/\Delta \geq 15 \right)$

[1] Wang CJ, Wen JX, Chen ZB, Dembele S. Int. J. Hyd Energy, 39 ,2014, p. 20560–9.
[2] Wang CJ, Liu HR, Wen JX. Applied Thermal Engineering 2018;129:1435–46.

Structure of fire whirl



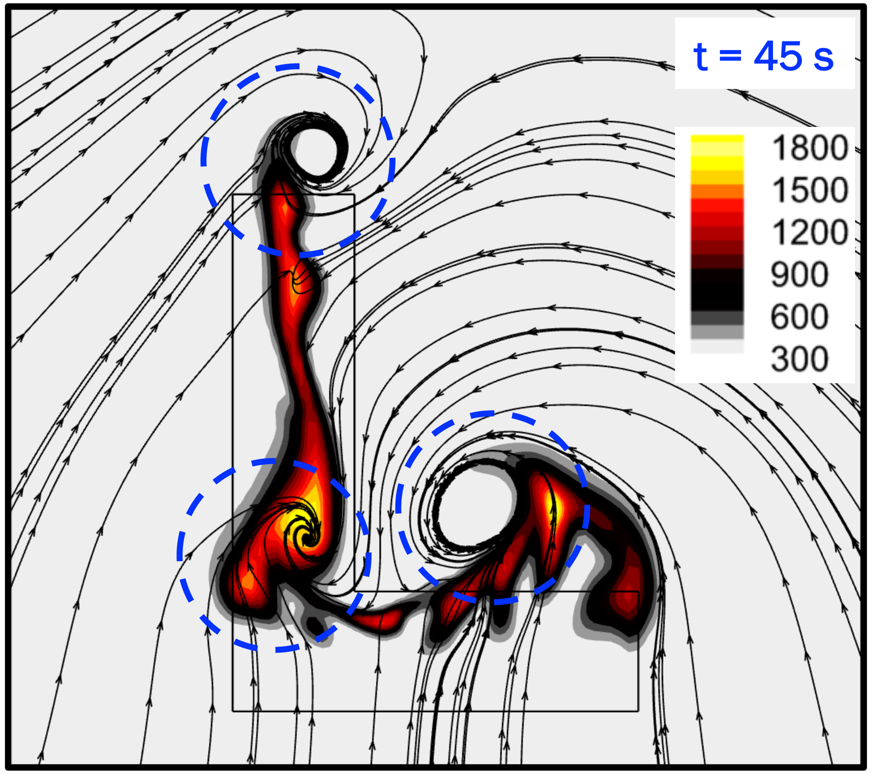
Temperature (K) contour with streamlines at 0.1 m above ground surface

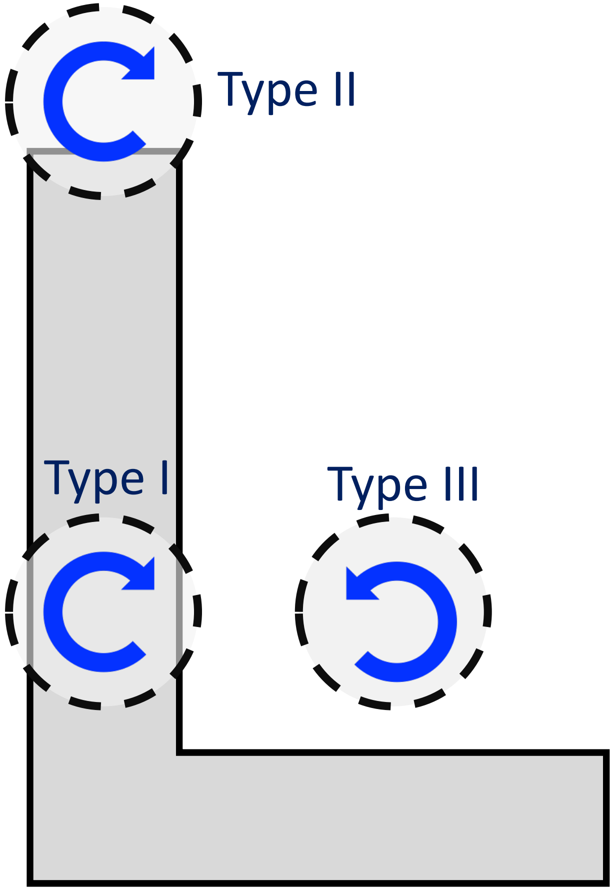


Temperature (K) contour with streamlines at 0.1 m above ground surface
Wind velocity = 0.05 m/s

Type I and II : Clockwise rotation

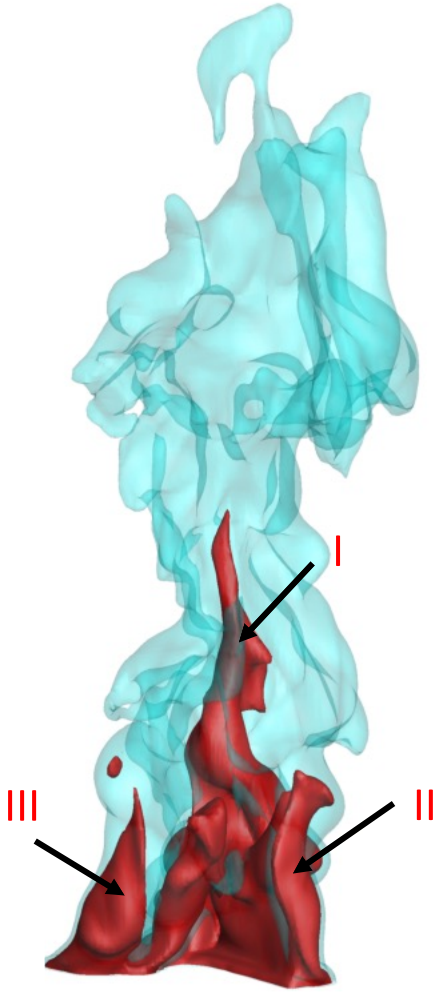
Type III : Anti-Clockwise rotation





H_2O isovalue 0.005

Temp isovalue 600 K



Mechanism of vorticity generation

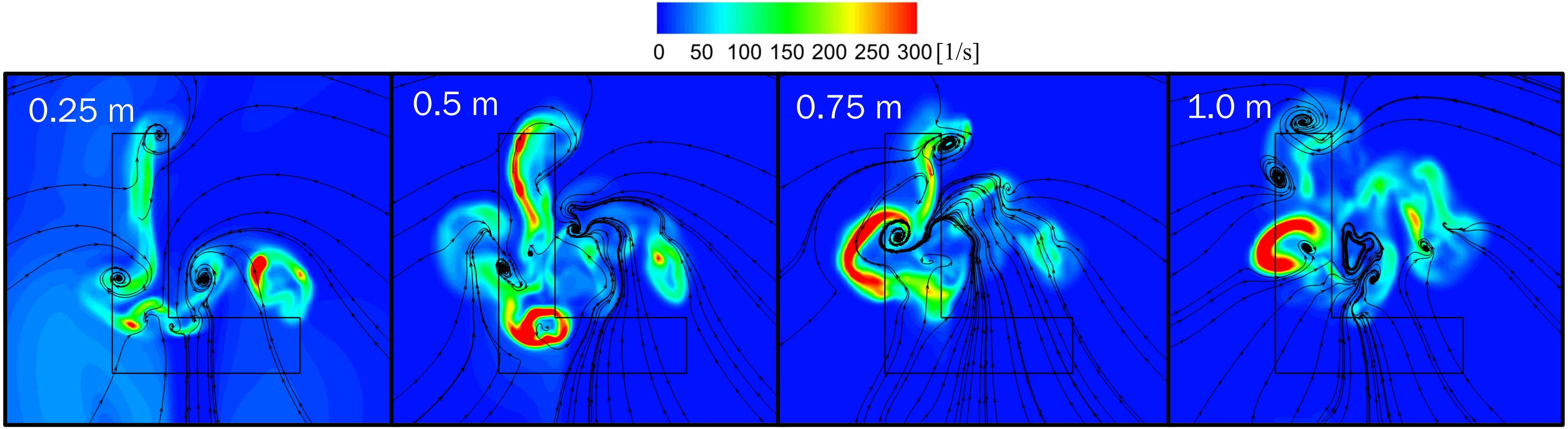
Vorticity Equation[1]

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \underbrace{(\mathbf{U}\cdot\nabla)\boldsymbol{\omega}}_{\text{Convection}} = \underbrace{(\boldsymbol{\omega}\cdot\nabla)\mathbf{U}}_{\text{Tilting}} - \underbrace{\boldsymbol{\omega}(\nabla\cdot\mathbf{U})}_{\text{Stretching}} + \underbrace{\frac{1}{\rho^2}\nabla\rho\times\nabla p}_{\text{Baroclinic}} + \underbrace{\nabla\times\left(\frac{\nabla\cdot\hat{\tau}}{\rho}\right)}_{\text{Traction forces}} + \underbrace{\nabla\times\mathcal{F}_{\mathrm{B}}}_{\text{Body forces}}$$

- Body forces: Change due to external forces
- Traction forces: Diffusion of vorticity due to viscous effects
- Baroclinic: Change in vorticity due to intersection of density and pressure surface
- Stretching: Stretching of vorticity due to flow compressibility
- Tilting: Tilting due to flow velocity gradient
- Convection: Change due to motion of fluid

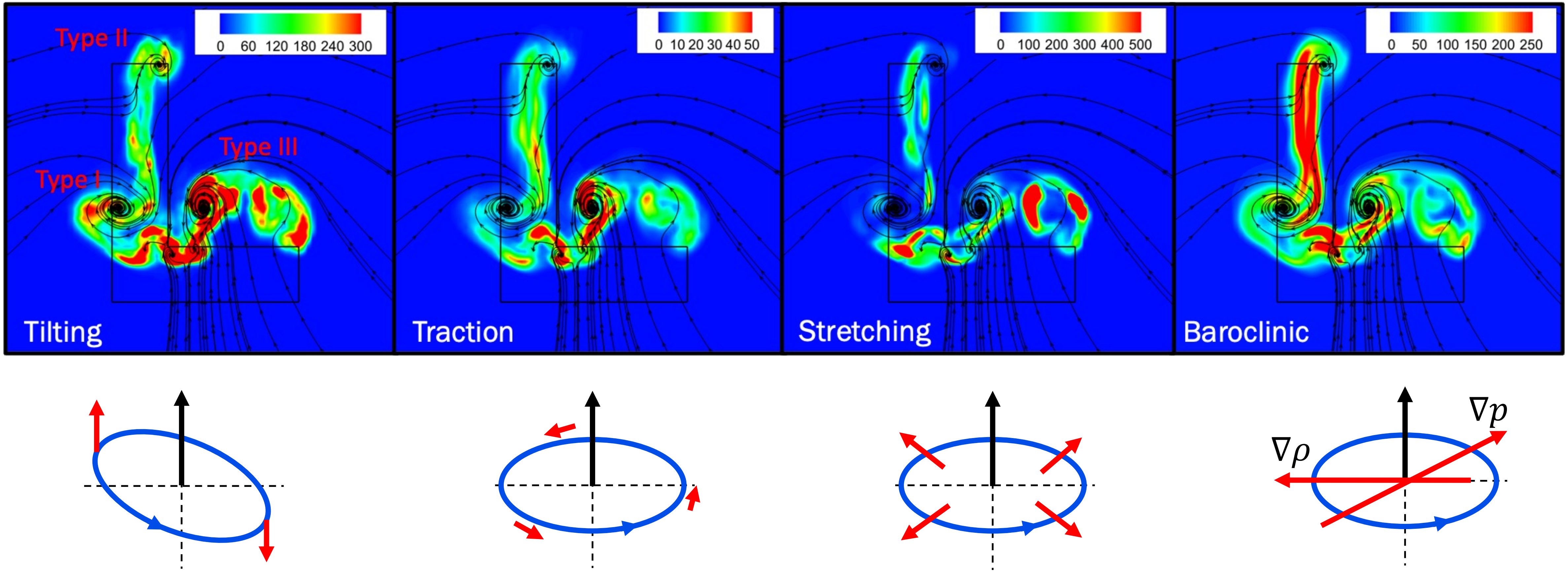
[1] Tohidi A., Gollner M., Xiao H., Annual Review of Fluid Mechanics, 2018, 50:187-213.

Vorticity field at various vertical slices



The vorticity is found in the vicinity of the fire source as expected.

Contributors to vorticity



Future directions

- Scope of further detailed analysis of the fire whirl generation
- Simulations with advanced combustion models incorporating a detailed chemical mechanism
- Simulation of small-scale fire whirl to understand the turbulence-chemistry interaction processes

Conclusions

- Three different types of fire whirls are generated over the L-shaped fire source in a crossflow are predicted
- Critical cross-flow velocity causes the generation of fire whirls
- Type I and Type II whirls are mainly generated due to Baroclinic torque
- Type III whirls are generated due to Tilting, Traction and stretching effects

Thank You

Acknowledgements