Evaluation of Fluid Thermal Systems by Dynamic Data Driven Application Systems

D. Knight, T. Rossman and Y. Jaluria
Department of Mechanical and Aerospace Engineering
Rutgers - The State University of New Jersey

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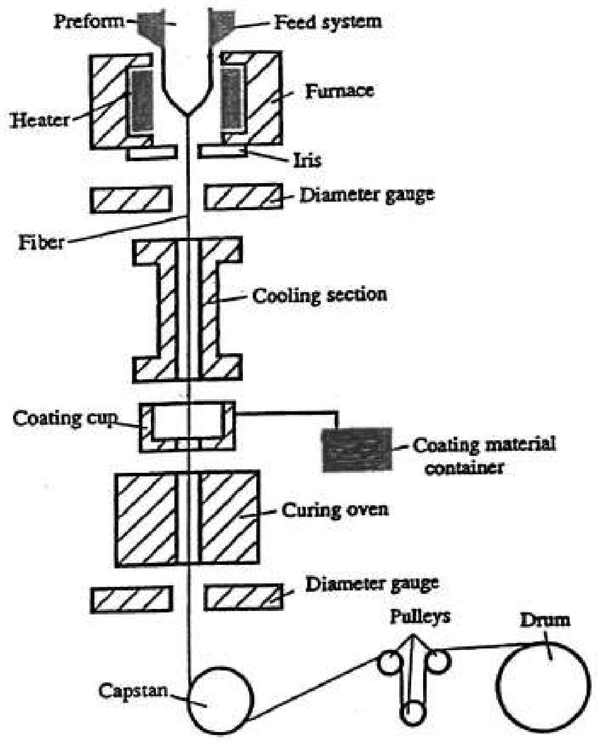
Outline

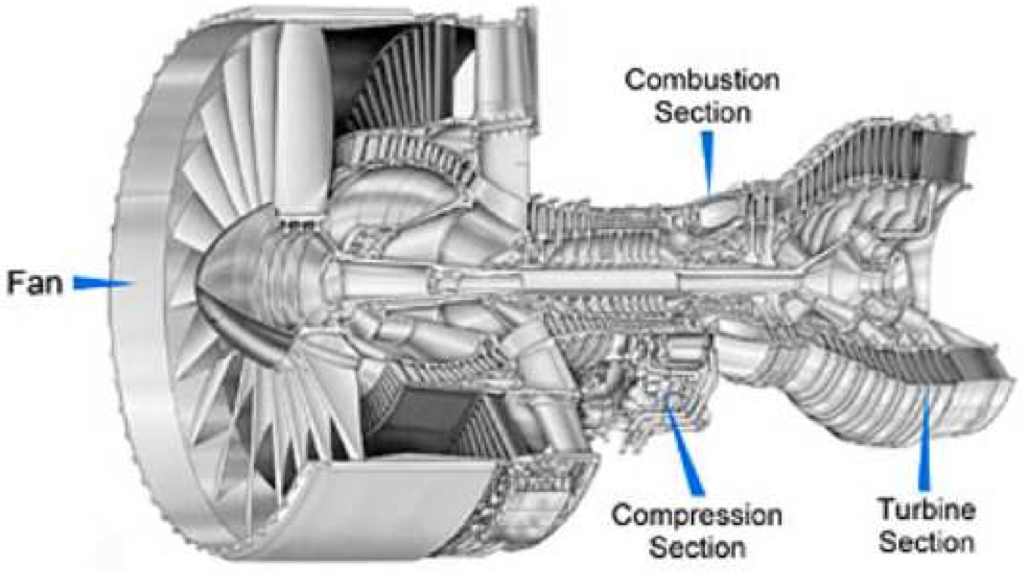
- Introduction
- Problem Definition
- Dynamic Data Driven Applications System Methodology
- Results
- Current Focus of Research
- Conclusions

Introduction

- In many engineering applications involving fluid-thermal systems, detailed quantitative infomation on the flow, temperature and species concentration is needed for system optimization



Optical fibre furnace

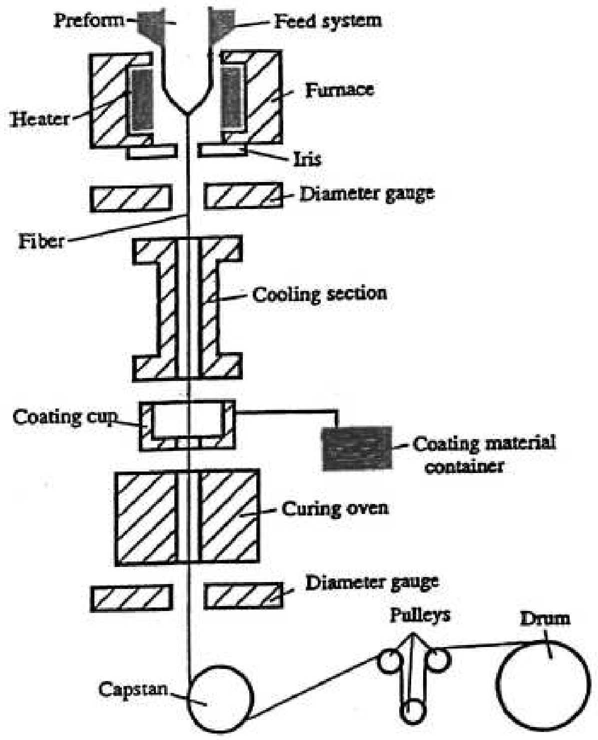


Turbofan engine

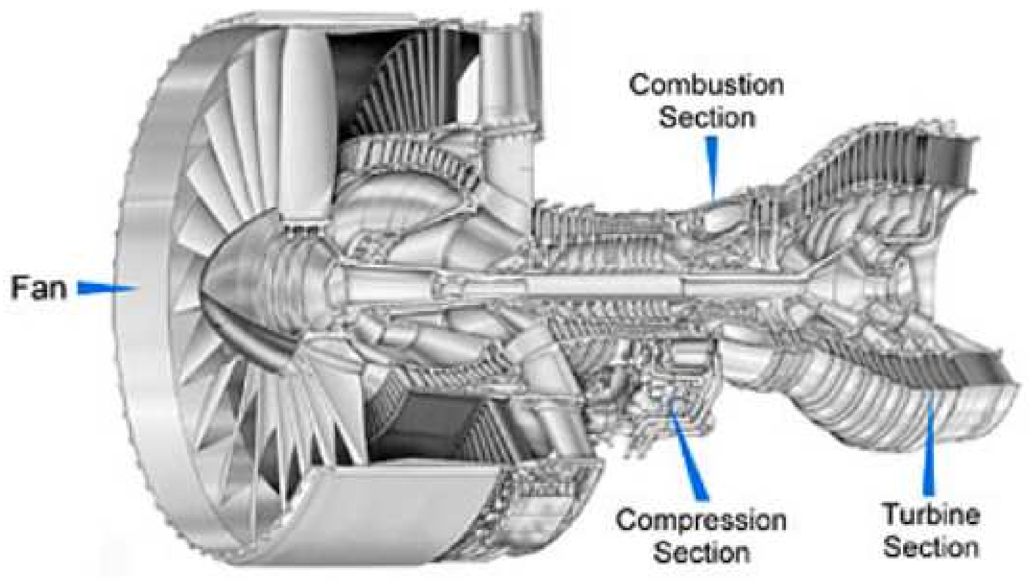
Introduction

- Numerical simulation can obtain the desired information and thus optimize the system

  However, this approach requires well-defined boundary and operating conditions which may not be completely known due to limited access for experimental measurements



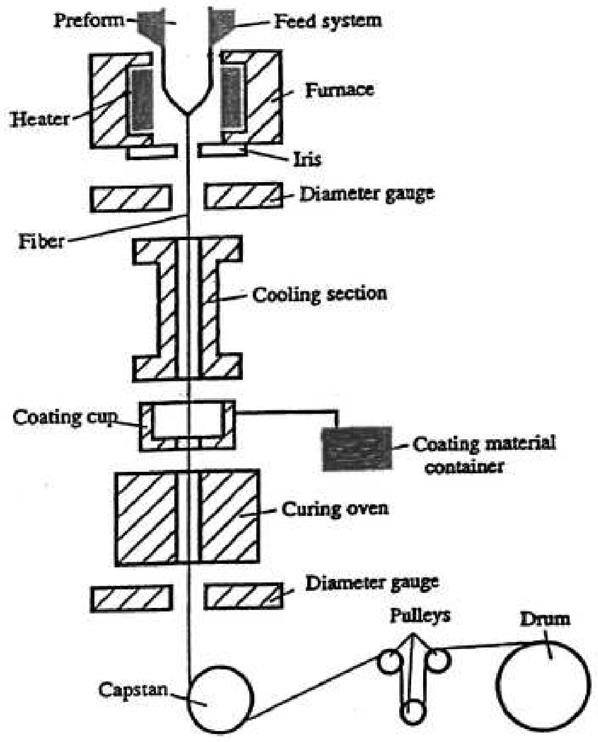
Optical fibre furnace



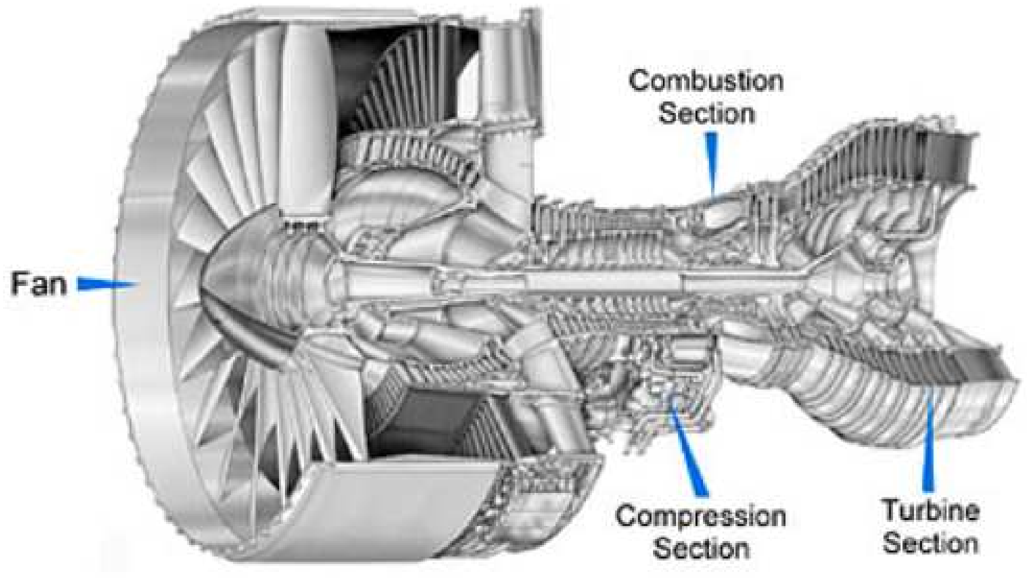
Turbofan engine

Introduction

- The objective of our research is to develop a Dynamic Data Driven Applications System approach that synergizes experiment and simulation to determine the boundary and operating conditions, thereby achieving a full simulation capability



Optical fibre furnace



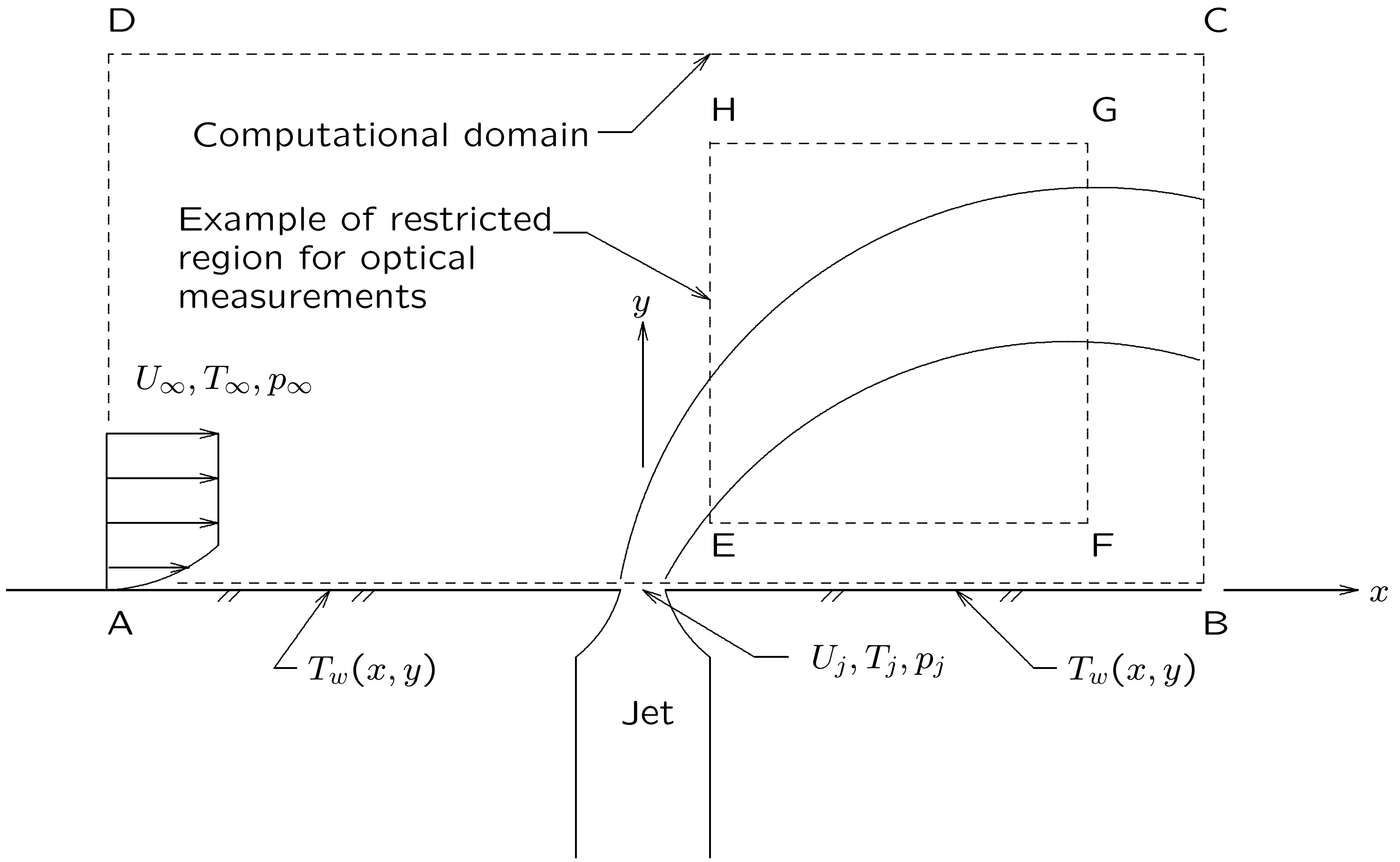
Turbofan engine

Problem Definition

Jet in Crossflow

- Heated wall jet in crossflow

  The objective is to determine the jet inflow conditions (U_j, T_j and p_j) using a Dynamic Data Driven Applications Systems method that synergizes experiment and simulation



Parameters

Item	*Known*	*Unknown*
U_∞	$\surd$	
T_∞	$\surd$	
p_∞	$\surd$	
U_j		$\surd$
T_j		$\surd$
p_j		$\surd$

Problem Definition

Jet in Crossflow

- Experiment

  Rutgers Low Speed Wind Tunnel

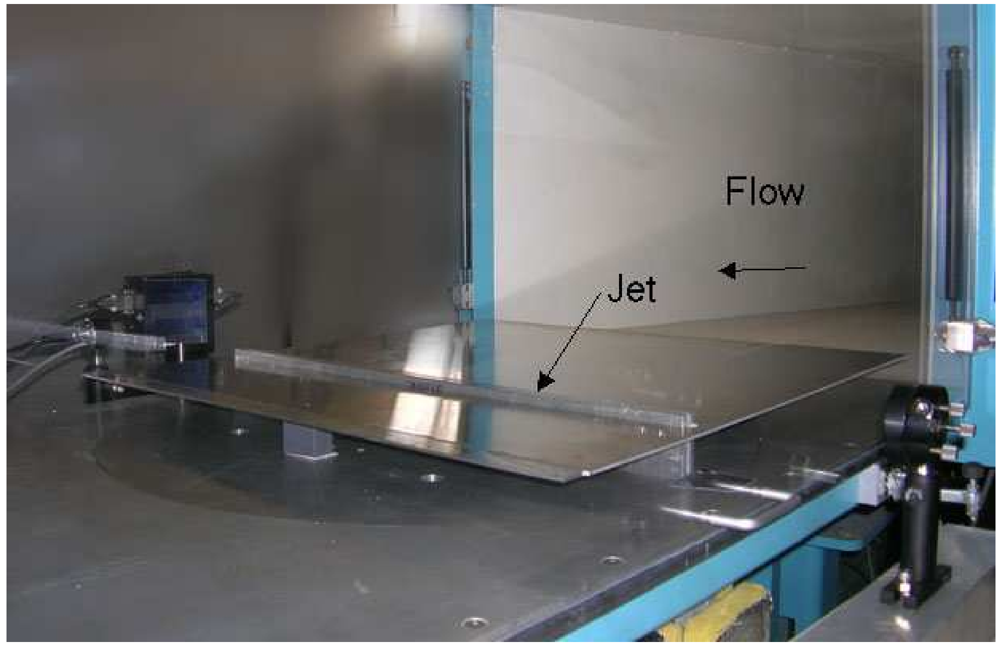
  Non-intrusive laser diode measurement

  Measure absorbance *vs* time at fixed (x, y)

  Static temperature T *vs* time from absorbance

  Limited region for absorbance measurement

  Each (x, y) measurement requires $\approx$ 1 hr



Experimental configuration

Problem Definition

Jet in Crossflow

- Laser diode absorbance

Instantaneous absorbance

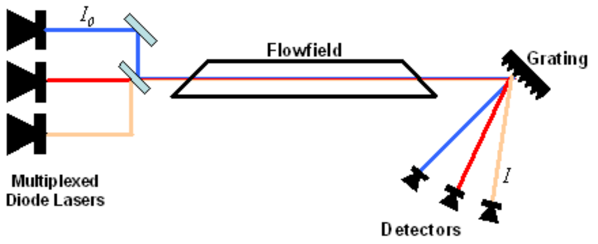
$$\mathcal{A}(x,y) = \frac{(I_o - I(x,y,t))}{I_o}$$

where I_o is incident intensity at (x,y,z_1) and $I(x,y,t)$ is transmitted intensity at (x,y,z_2)

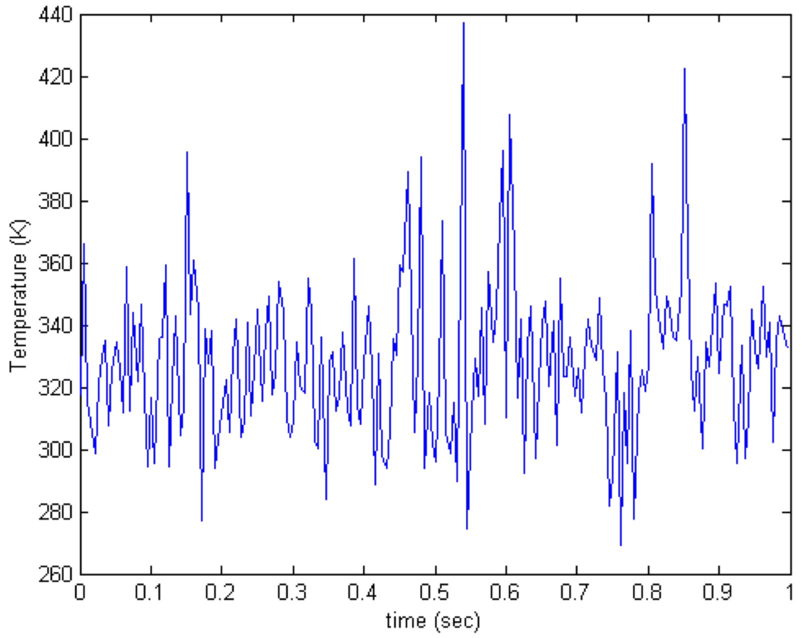
Absorbance per cm of the ${}^{Q}R_2(6)$ line of the oxygen transition $b_1\Sigma_g^+\nu' = 0 \leftarrow X^3\Sigma_g^-\nu'' = 0$ at 761.139 nm is

$$\frac{d\mathcal{A}}{dz} = 0.083\,T^{-1} - 2.26 \cdot 10^{-5}$$

where $T(x,y,z,t)$ is the static temperature in K



Laser diode arrangement



Typical T *vs* time

Problem Definition

Jet in Crossflow

- Simulation

  Laminar Navier-Stokes equations

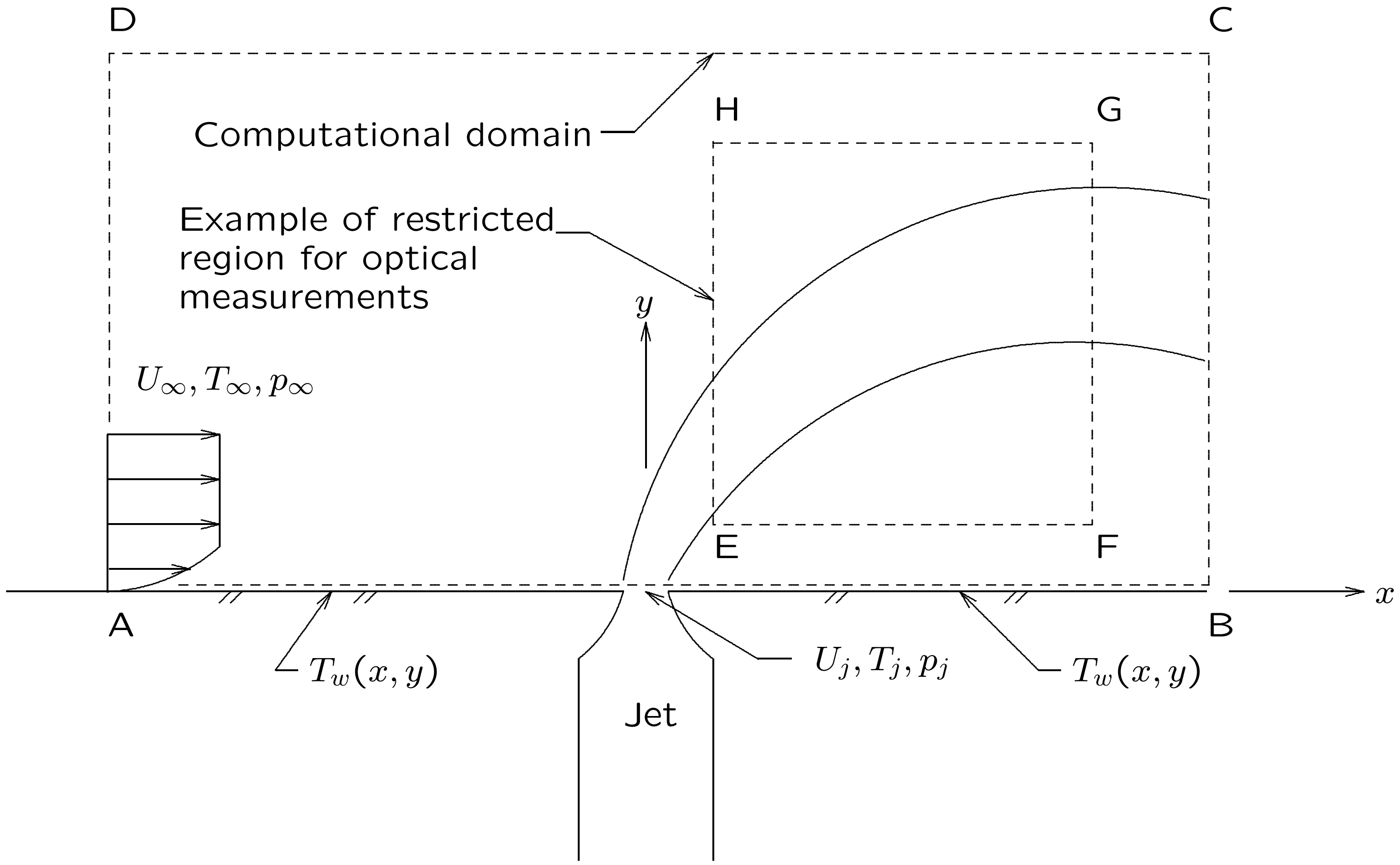
  Incompressible, ideal gas

  Unsteady, time-dependent

  Sutherland viscosity law

  Fluent©

  Parallel (8 processors)



Problem Definition

Jet in Crossflow

- Assumptions

  Large set $\mathcal{D}$ of discrete data locations defined ($\leq$ no. of grid cells in simulation)

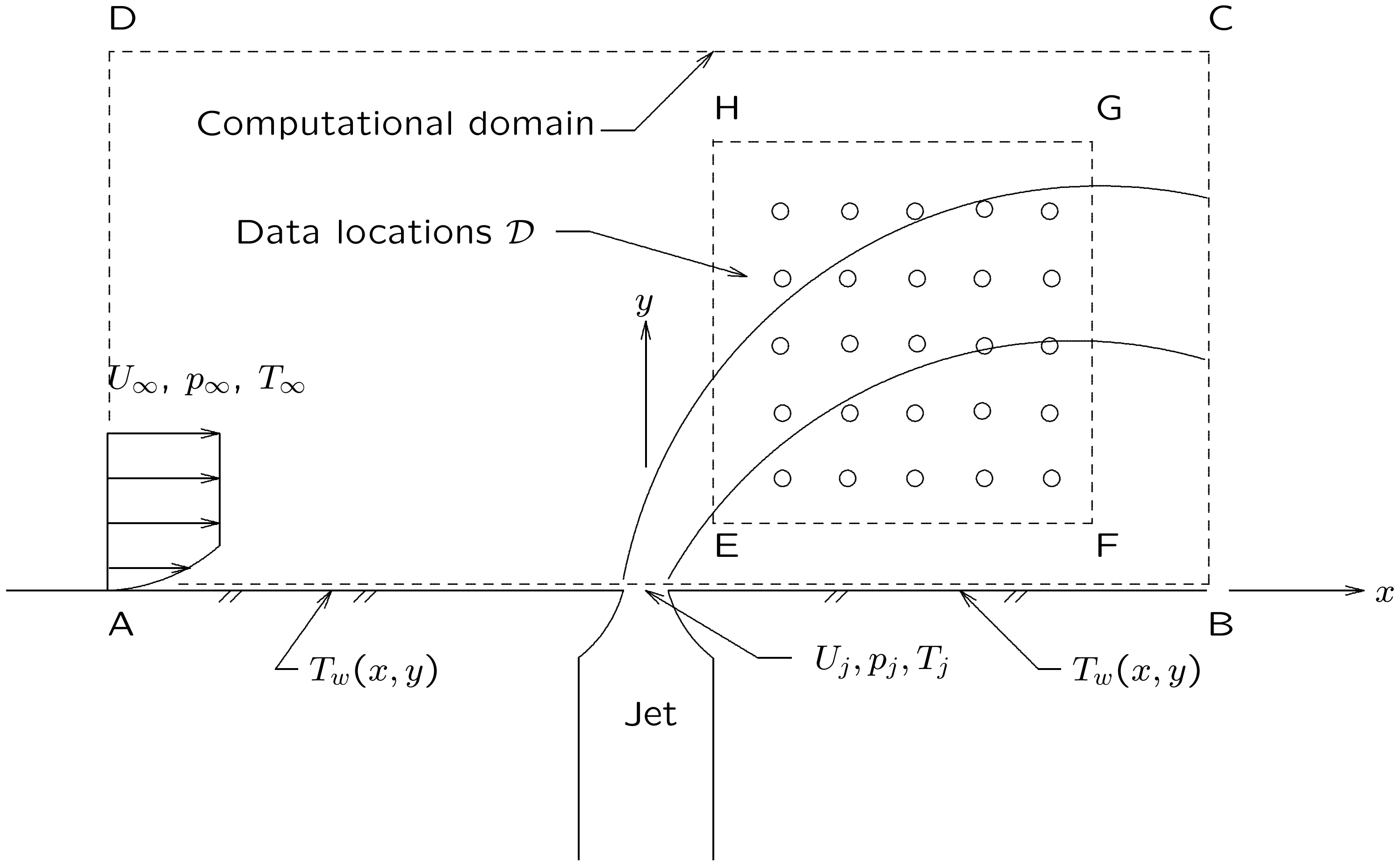
  For each experiment $\mathcal{E}_\nu$, time series data obtained for small subset $\mathcal{D}_\nu$ of locations

  For each simulation $\mathcal{S}_\nu$, time series data obtained for entire set $\mathcal{D}$ for U_{j_ν}, p_{j_ν}, T_{j_ν}

- The quantity for comparison between experiment and simulation is the mean square temperature fluctuations $\overline{T'^2}$

- Problem

  What is the optimum sequence of simulations and experiments to determine U_j, T_j, p_j ?



Dynamic Data Driven Applications System Methodology

- Algorithm

```
Build initial Response Surface models $\mathcal{M}_1$ for $\overline{T'^2}$ on $\mathcal{D}$ using simulation assumed values for
$U_j$, $p_j$, $T_j$

Select $\mathcal{D}_1$ randomly from $\mathcal{D}$

loop in $\nu$ beginning with $\nu = 1$ until converged
{
    Perform experiment $\mathcal{E}_\nu$ and obtain $\overline{T'^2}$ on $\mathcal{D}_\nu$

    Use Response Surface models $\mathcal{M}_\nu$ for $\overline{T'^2}$ on $\mathcal{D}_\nu$ to predict $U_{j_{\nu+1}}$, $p_{j_{\nu+1}}$, $T_{j_{\nu+1}}$
    based on experiment $\mathcal{E}_\nu$

    Perform simulation $\mathcal{S}_{\nu+1}$ using $U_{j_{\nu+1}}$, $p_{j_{\nu+1}}$, $T_{j_{\nu+1}}$ and update Response Surface Models $\mathcal{M}_{\nu+1}$

    Select $\mathcal{D}_{\nu+1}$ based upon largest values of $\overline{T'^2}$ on $\mathcal{D}$ from Response Surface Models $\mathcal{M}_{\nu+1}$
}
```

Results

Flowfield Structure

- The flowfield is inherently unsteady

Item	*Value*
U_∞ (m/s)	4
T_∞ (K)	290
p_∞ (atm)	1
U_j (m/s)	8
T_j (K)	370
p_j (atm)	1

Temperature contours

Results

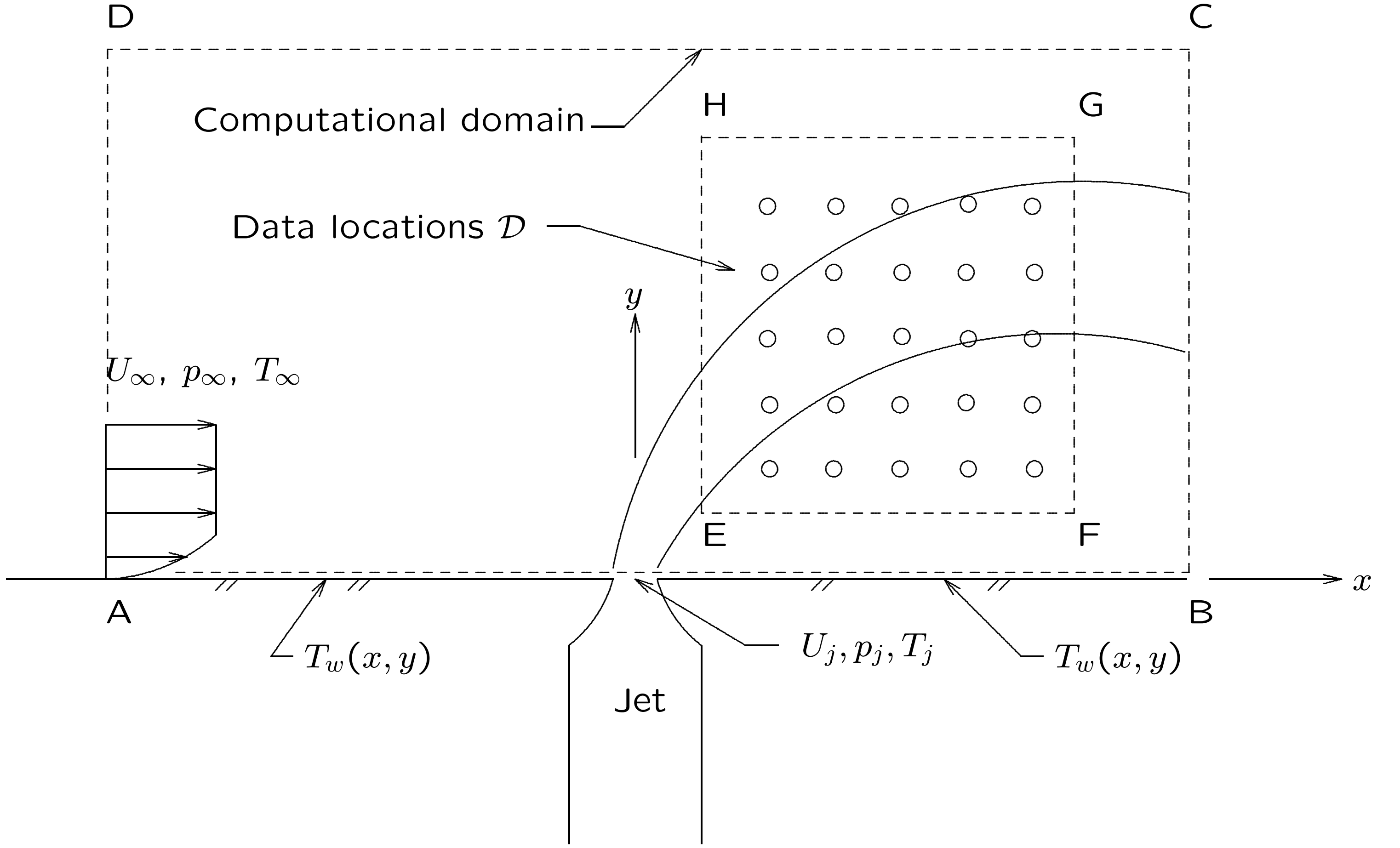
Simple Test of Algorithm

- Pseudo-experiment performed to generate T *vs* time at 18 locations

Parameters

Item	*Value*
U_∞ (m/s)	4
T_∞ (K)	290
p_∞ (atm)	1
U_j (m/s)	8
T_j (K)	"unknown"
p_j (atm)	1

- Questions
  - What is the effect of the signal level on accuracy of Response Surface model ?
  - What is the required duration for the time series ?



Results

Simple Test of Algorithm

- Step No. 1

  The initial values of T_j for Response Surface selected at random from $290 < T_j < 500$

  The initial locations for "measurement" selected at random from matrix of 18 locations (3 horizontal rows of 6 points each)

		$\overline{T'^2}$ (K^2)			
Case	T_j (K)	Location 7	Location 10	Location 12	Location 13
Experiment No. 1	"unknown"	392.6	286.8	207.4	120.1
1	405	762.0	543.7	358.5	112.7
2	356	305.2	142.2	104.7	115.6
$T_j\big\vert_{\text{predicted}}$		365.3	373.6	375.8	$\rightarrow$ 281.1

Average $T_j\big\vert_{\text{predicted}}$	349 K
Std Dev $T_j\big\vert_{\text{predicted}}$	45.4 K

Results

Simple Test of Algorithm

- Step No. 1 (cont'd)

		$\overline{T'^2}$ (K^2)			
Case	T_j (K)	Location 7	Location 10	Location 12	Location 13
Experiment No. 1	"unknown"	392.6	286.8	207.4	120.1
1	405	762.0	543.7	358.5	112.7
2	356	305.2	142.2	104.7	115.6
$T_j\big\vert_{\text{predicted}}$		365.3	373.6	375.8	→ 281.1

Average $T_j\big\vert_{\text{predicted}}$	349 K
Std Dev $T_j\big\vert_{\text{predicted}}$	45.4 K

Revised $T_j\big\vert_{\text{predicted}} = 372$ discarding values that are more than one standard deviation from mean

The revised locations for experimental measurement based upon the highest values of $\overline{T'^2}$ from Cases 1 and 2 are Locations 1, 2, 7 and 8

Results

Simple Test of Algorithm

- Step No. 2

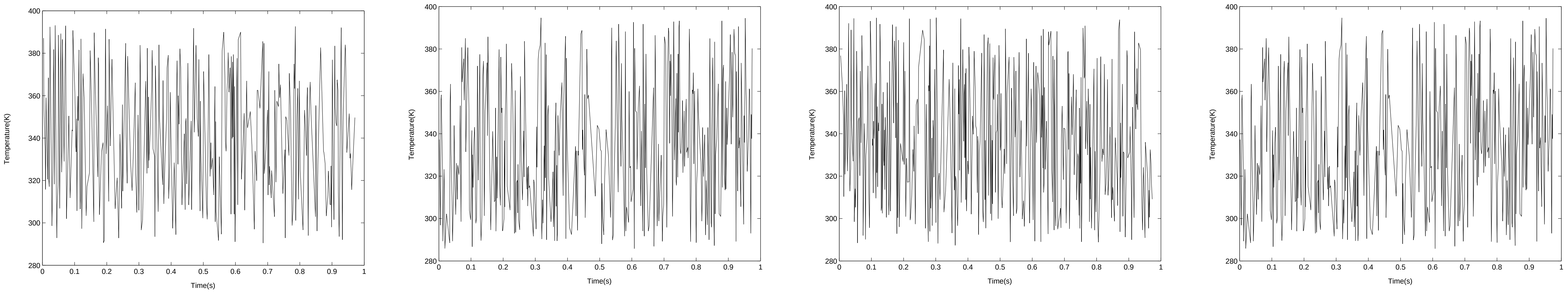
		$\overline{T'^2}$ (K^2)			
Case	T_j (K)	Location 1	Location 2	Location 7	Location 8
Experiment No. 2	"unknown"	408.4	272.1	392.6	381.7
1	405	1035.2	641.8	762.0	617.1
2	356	303.6	224.3	305.2	224.0
3	367	358.4	253.1	390.8	303.9
$T_j\big\vert_{\text{predicted}}$		376.0	367.2	373.7	377.2

Average $T_j\big\vert_{\text{predicted}}$	373.5 K
Std Dev $T_j\big\vert_{\text{predicted}}$	4.4 K
Experiment	370 K

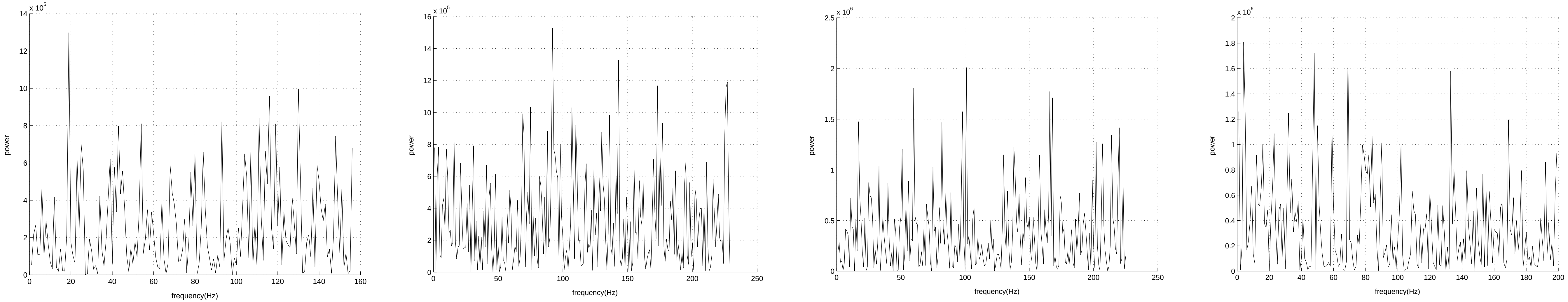
Results

Typical Experimental Results

Temperature *vs* time



Power spectrum of temperature fluctuations



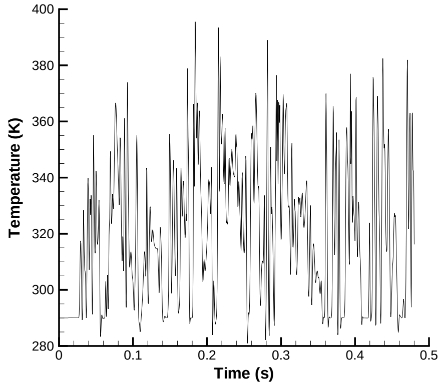
$(x, y) = (0.218\text{m}, 0.03\text{m})$ $(x, y) = (0.228\text{m}, 0.03\text{m})$ $(x, y) = (0.238\text{m}, 0.03\text{m})$ $(x, y) = (0.238\text{m}, 0.04\text{m})$

Results

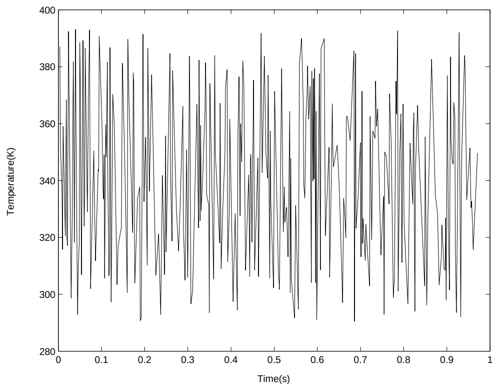
Comparison of Computation and Experiment

Temperature *vs*˙ time

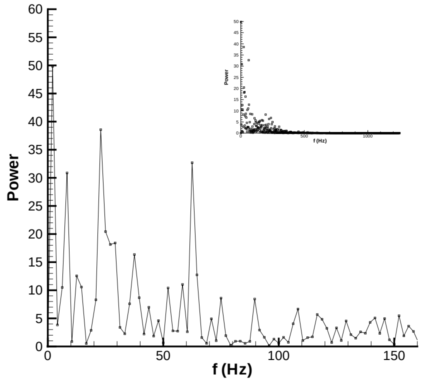
Power spectrum



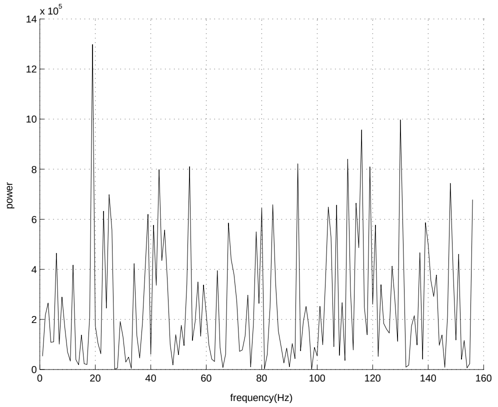
Computation



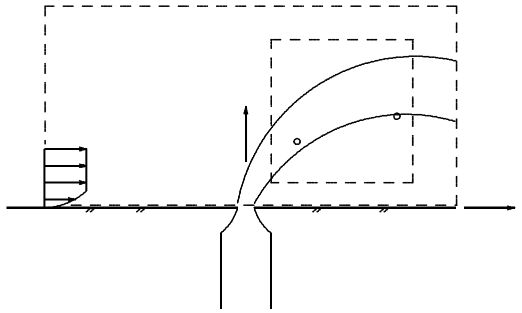
Experiment



Computation



Experiment



- Difference in spectra at higher frequencies due to three-dimensional effects in experiment

  Jet “undulating” in spanwise direction

- What is the effect of the simulation model accuracy on accuracy of Response Surface model ?

Current Focus of Research

- Two issues need to be addressed in systematic manner regarding the accuracy of the Response Surface model
  - Signal level

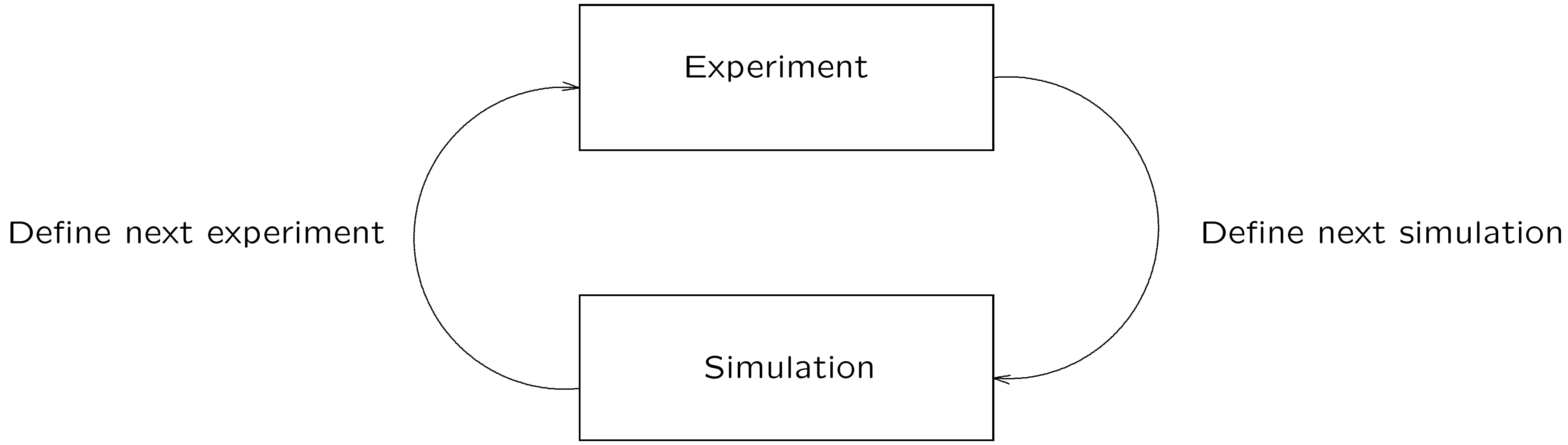
    Currently using simple statistical model to discard unrealistic predicted values for U_j, p_j, T_j
  - Accuracy of simulation model

    Need to incorporate the uncertainty of the simulation model into the DDDAS methodology

    The uncertainty in the simulation model affects:
    - The uncertainty in the predicted boundary conditions
    - The convergence criteria for the DDDAS methodology
- The jet in crossflow is a good configuration for evaluating method addressing these issues

Conclusions

- Developing DDDAS methodology for evaluation of fluid thermal systems
  - Examples are optical fibre furnace and turbofan combustor
  - Need for complete flowfield simulation to optimize system performance
  - Boundary conditions for flowfield simulation are not completely known *a priori*
  - Non-intrusive optical measurements (*e.g.*, laser diode absorbance) feasible in limited region
  - DDDAS method to determine complete boundary conditions by synergizing experiment and simulation



Experiment

Define next experiment

Define next simulation

Simulation