Subtask 3.1D

Measurement and Analysis of Integral Length Scale and Turbulence Viscosity in a Rapid Compression/Expansion Machine Using PIV

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Background and Motivation of the Study - 1 of 2

- The integral length scale is one of the important factors to characterize the turbulence in engine cylinders.
  - $\varepsilon = C' k^{3/2}/L$ $\quad$ k : turbulence kinetic energy

    $\nu_t = C_\mu^{1/4} k^{1/2} L$ $\quad$ ε : turbulence kinetic energy dissipation rate

    L : integral length scale

    ν_t : turbulence kinematic viscosity

    $C' = 0.169 \sim 0.201$, $C_\mu = 0.09$

  - Measurements of k and L provide all other turbulence characteristics.

- There have been many k data measured in engine cylinders with HWA, LDV or PIV. The measurements of L, however, have been limited in number.

Background and Motivation of the Study - 2 of 2

- Cross-Correlation PIV
  - Spatial measurement of velocity
  - The Taylor hypothesis is not necessary to obtain *L*.
  - Free from the influence of pressure and temperature
  - Popular and well-established in measuring velocity fields.
  - The measurement of *L* is neither well-examined nor established.
  - Better utilization of PIV should be developed.

Purpose of the Study

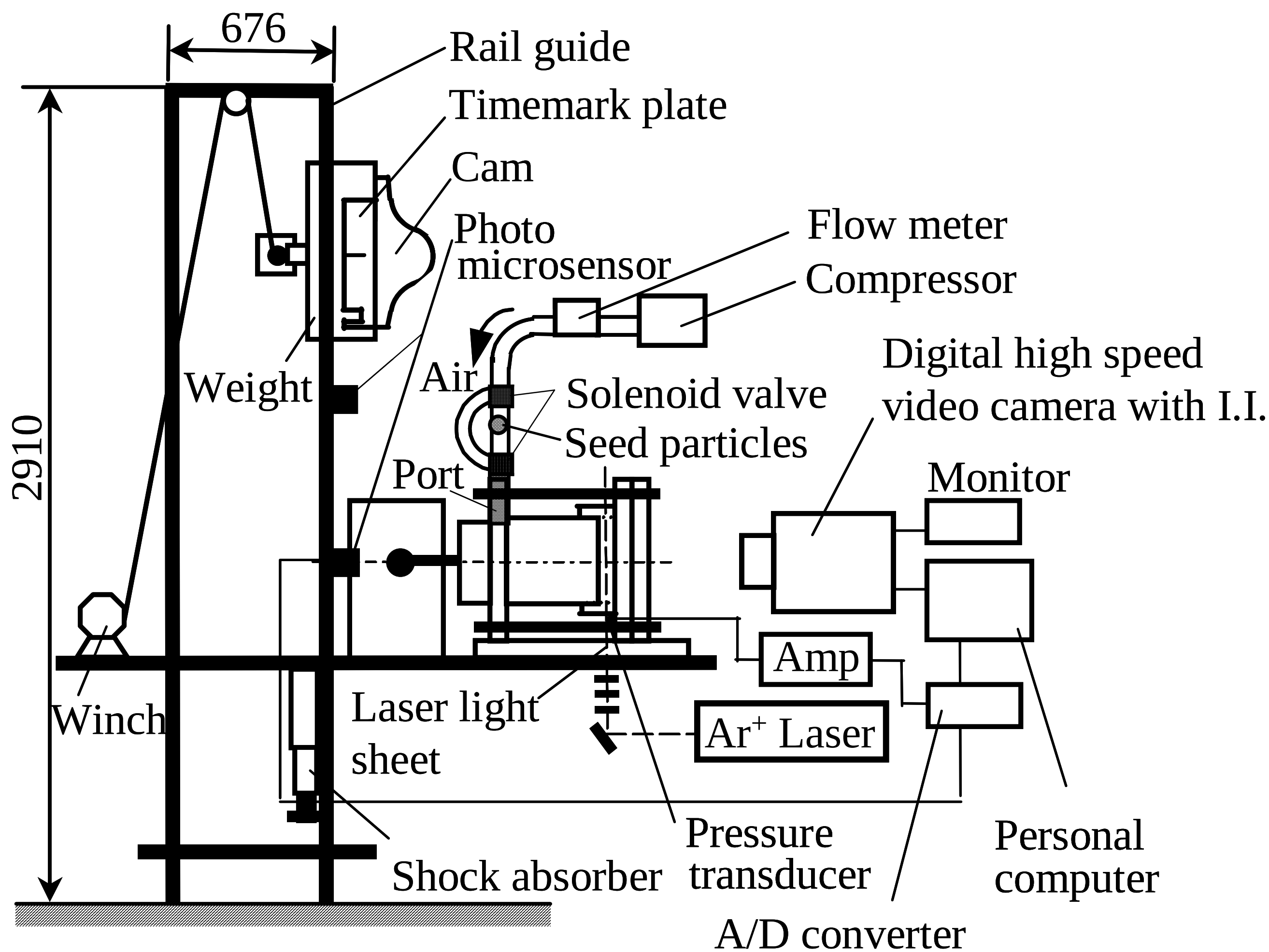
- To improve the cross-correlation technique for reliable data of integral length scale *L* in PIV

- To compare turbulence characteristics measured in a cylinder of a rapid compression/expansion machine including the turbulence kinetic energy, integral length scale and turbulence kinematic viscosity with computational results and to validate the model for dilatation effect during compression/expansion

Experimental Set-up

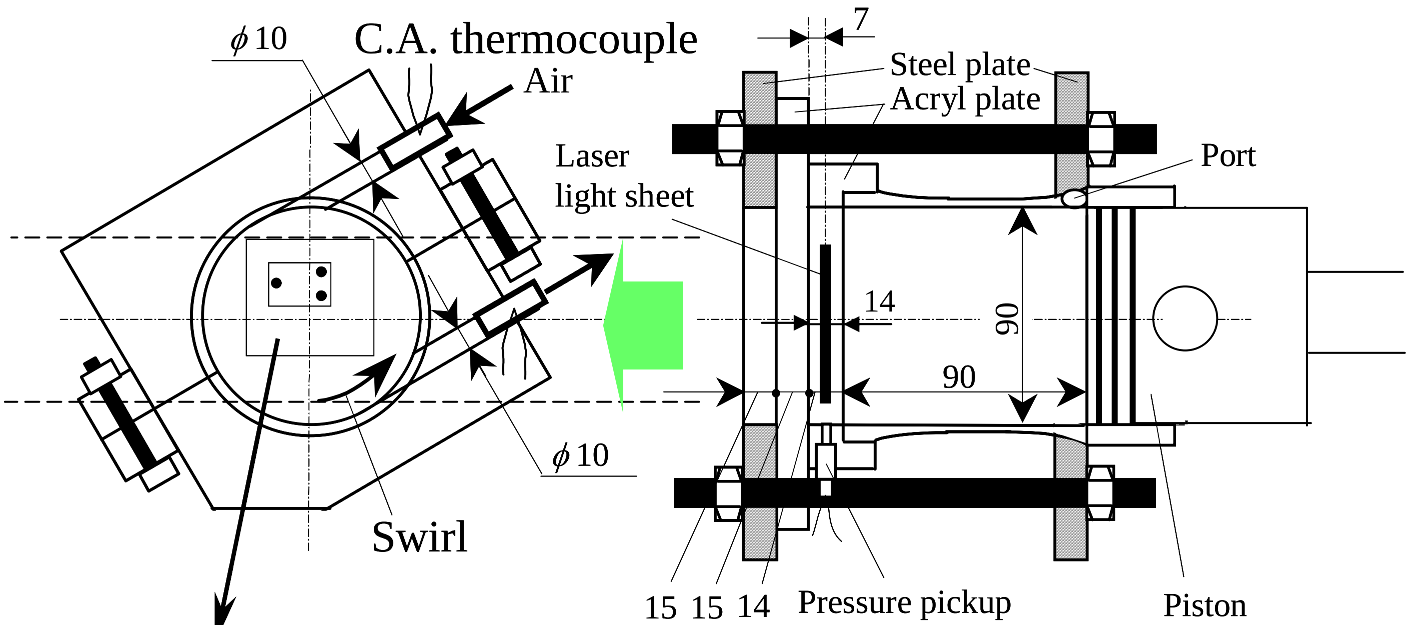
Equivalent engine speed:

1110 rpm



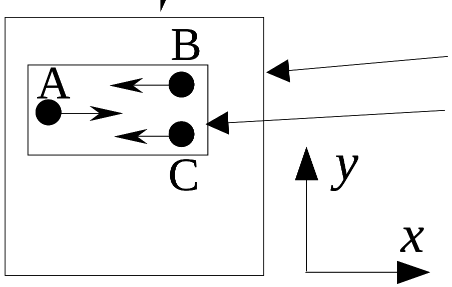
Rapid compression/expansion machine and PIV system

Experimental Set-up



Seeding particles: plastic hollow sphere with average diameter of 50 μm

Thickness of Laser light sheet : 1 mm



Region of picture, Size: 46.1 × 46.1

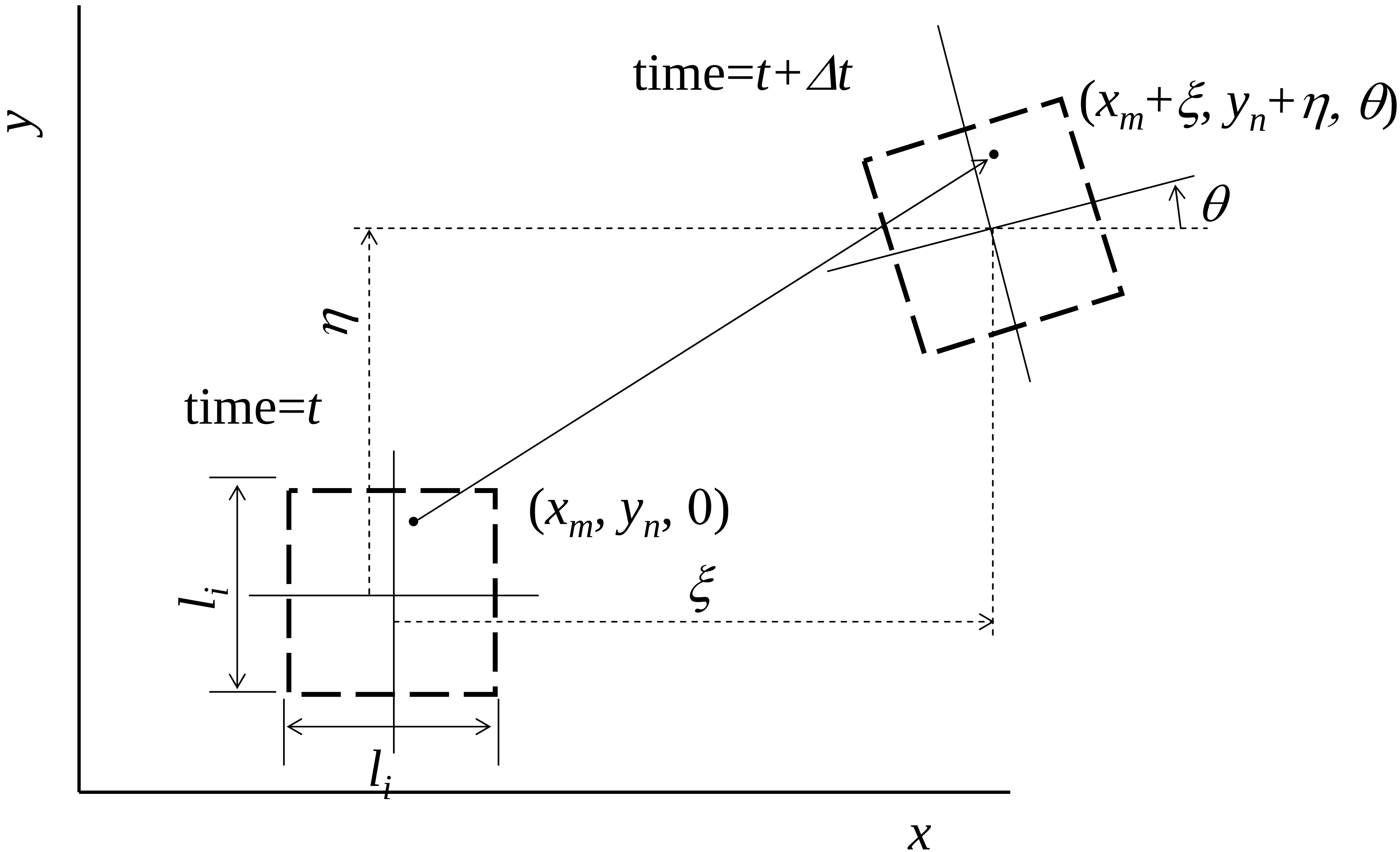
Region of analysis, Size: 32.4 × 16.2

● : Location for measuring integral length scale

1 pixel=0.18 mm × 0.18 mm

Cross sections of cylinder-piston assembly and three locations, A, B and C, for integral length scale measurements

Improved Cross-Correlation Technique



Improved Cross-Correlation

- Cross-Correlation

$$R(t+\Delta t,\xi,\eta,\theta) = \frac{\sum_m \sum_n \{I(t,x_m,y_n,0)\times I(t+\Delta t,x_m+\xi,y_n+\eta,\theta)\}}{\sqrt{\sum_m \sum_n I^2(t,x_m,y_n,0)}\times\sqrt{\sum_m \sum_n I^2(t+\Delta t,x_m+\xi,y_n+\eta,\theta)}}$$

I: local brightness of image, θ: rotation angle

- $R_0(t+\Delta t,\xi_0,\eta_0,\theta_0)$: maximum of $R(t+\Delta t,\xi,\eta,\theta)$

  ξ_0,η_0 : average parallel movement of gas blob of a template size

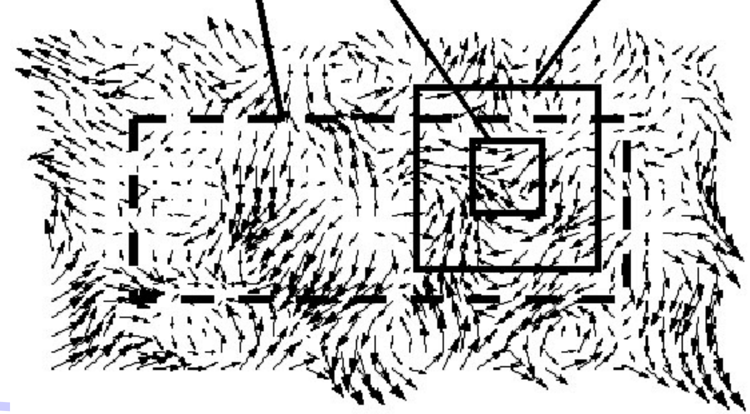
  θ_0 : average rotational angle of gas blob of a template size

Definition of Turbulence Intensity

- Turbulence intensity:
  Assumption of isotropic turbulence gives,

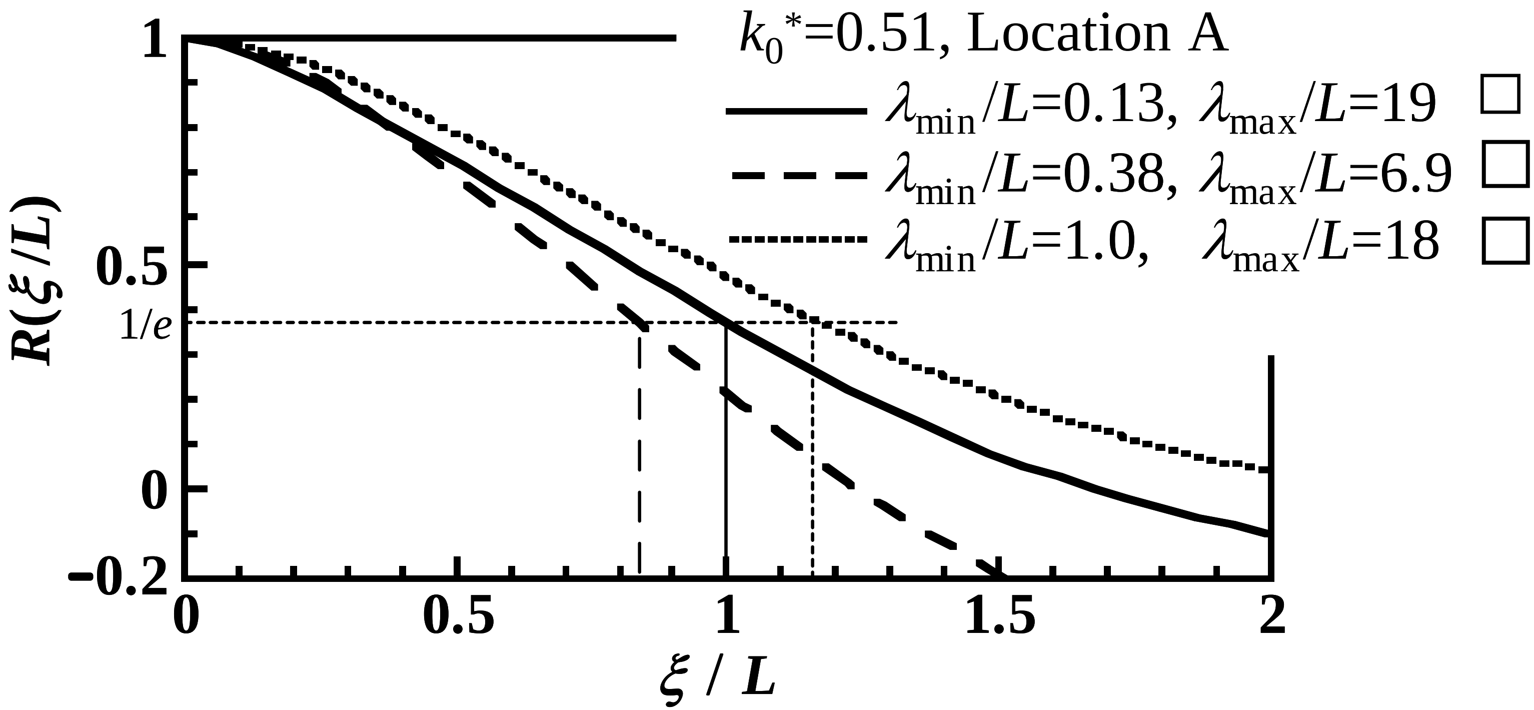
$$u^*(x,y) = \sqrt{\frac{3}{2l_m^2} \int_{-l_m/2}^{l_m/2} \int_{-l_m/2}^{l_m/2} \{\hat{u}(x+\xi, y+\eta)\}^2 d\xi d\eta}$$

$$\hat{u}(x,y) = \left| \vec{u}(x,y) - \vec{U}(x,y) \right|$$



u : local velocity
U: spatial average velocity
l_i: size of square template for u
l_m: size of square template for U

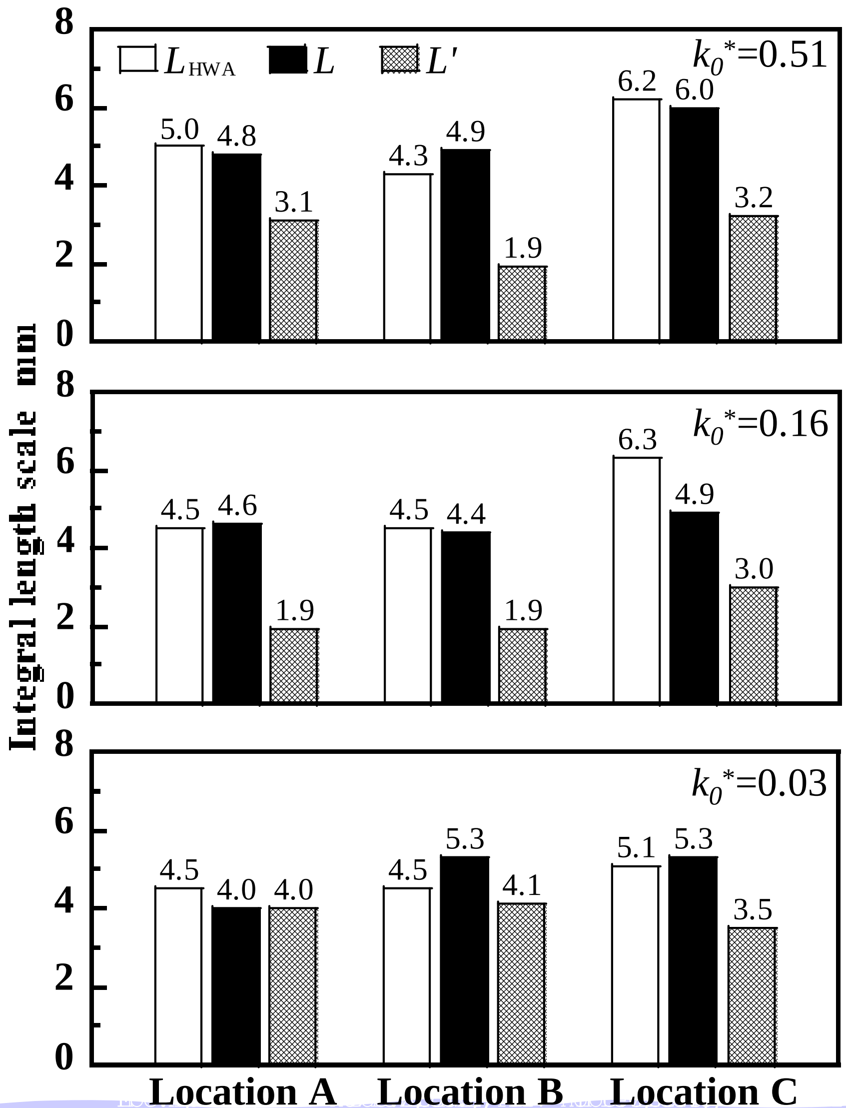
Estimation of Errors in Integral Length Scale measurements



λ_{min}: min. wave length, λ_{max}: max. wave length, L: integral length scale

- Spatial velocity data obtained from HWA data using Taylor hypothesis for steady flow at BDC position; the range of wave length is enough
- cut longer wave length
- cut shorter wave length

Comparison of Integral Length Scale



Integral length scales measured in steady flow test at BDC position by three different methods;

L_{HWA}: measured with HWA

L : taking θ into consideration

L' : leaving θ out of consideration (θ=0)

$k_0^* = k_0/C_m^2$

Standard *k–ε* two equation turbulence model

$$\boxed{\begin{aligned}\frac{\partial(\rho k)}{\partial t}+\nabla\cdot(\rho\vec{u}k)&=D_k+S_k\\ \frac{\partial(\rho\varepsilon)}{\partial t}+\nabla\cdot(\rho\vec{u}\varepsilon)&=D_\varepsilon+S_\varepsilon\end{aligned}}$$

$$D_k=\nabla\cdot\left(\frac{\mu_e}{\sigma_k}\nabla k\right)$$

$$D_\varepsilon=\nabla\cdot\left(\frac{\mu_e}{\sigma_\varepsilon}\nabla\varepsilon\right)$$

$$S_k=2\mu_t S_{ij}S_{ij}-\frac{2}{3}(\nabla\cdot\vec{u})\{\mu_e(\nabla\cdot\vec{u})+\rho k\}-\rho\varepsilon$$

$$S_\varepsilon=\frac{\varepsilon}{k}\left[2C_1\mu_t S_{ij}S_{ij}-\frac{2}{3}(\nabla\cdot\vec{u})\{C_1'\mu_e(\nabla\cdot\vec{u})+C_1''\rho k\}-C_2\rho\varepsilon\right]+\underbrace{C_3\rho\varepsilon(\nabla\cdot\vec{u})}_{\text{dilatation term}}$$

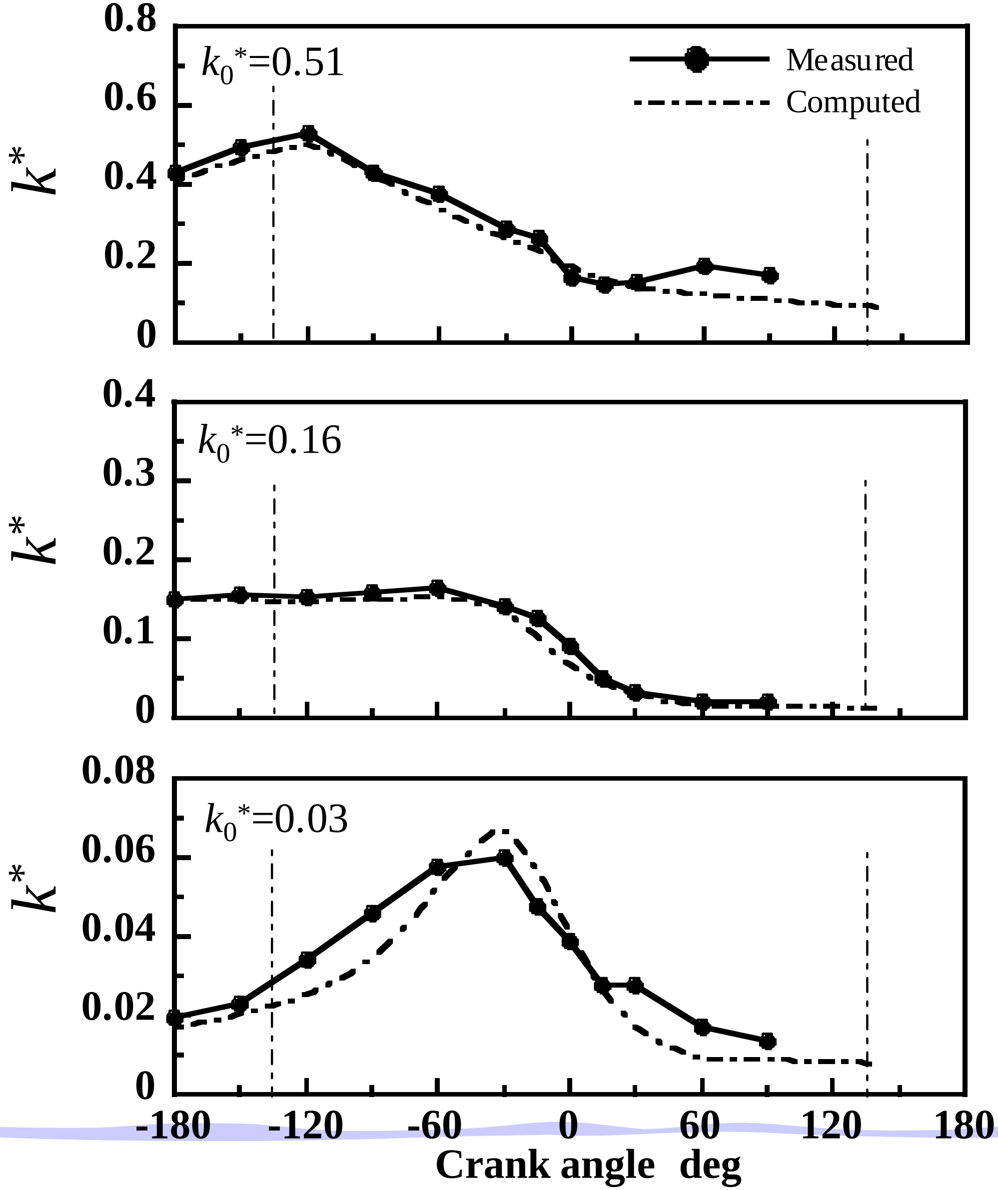
$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$

C_1=1.44、C_1’=1.32、C_1’’=4.50、C_2=1.92

$$\nabla\cdot\vec{u}=S_{ii}$$

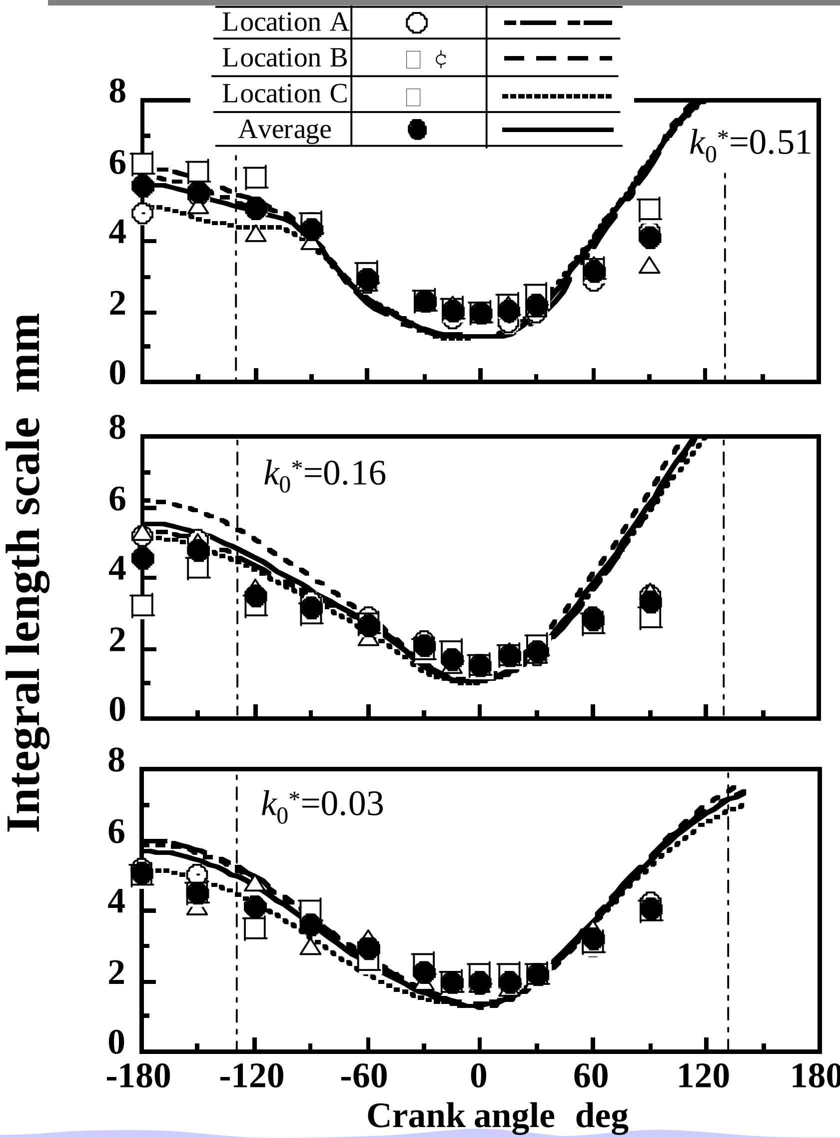
<u>C_3=1.0</u> : Morel-Mansour model for one-dimensional comp./exp.

Comparison of Turbulence Kinetic Energy

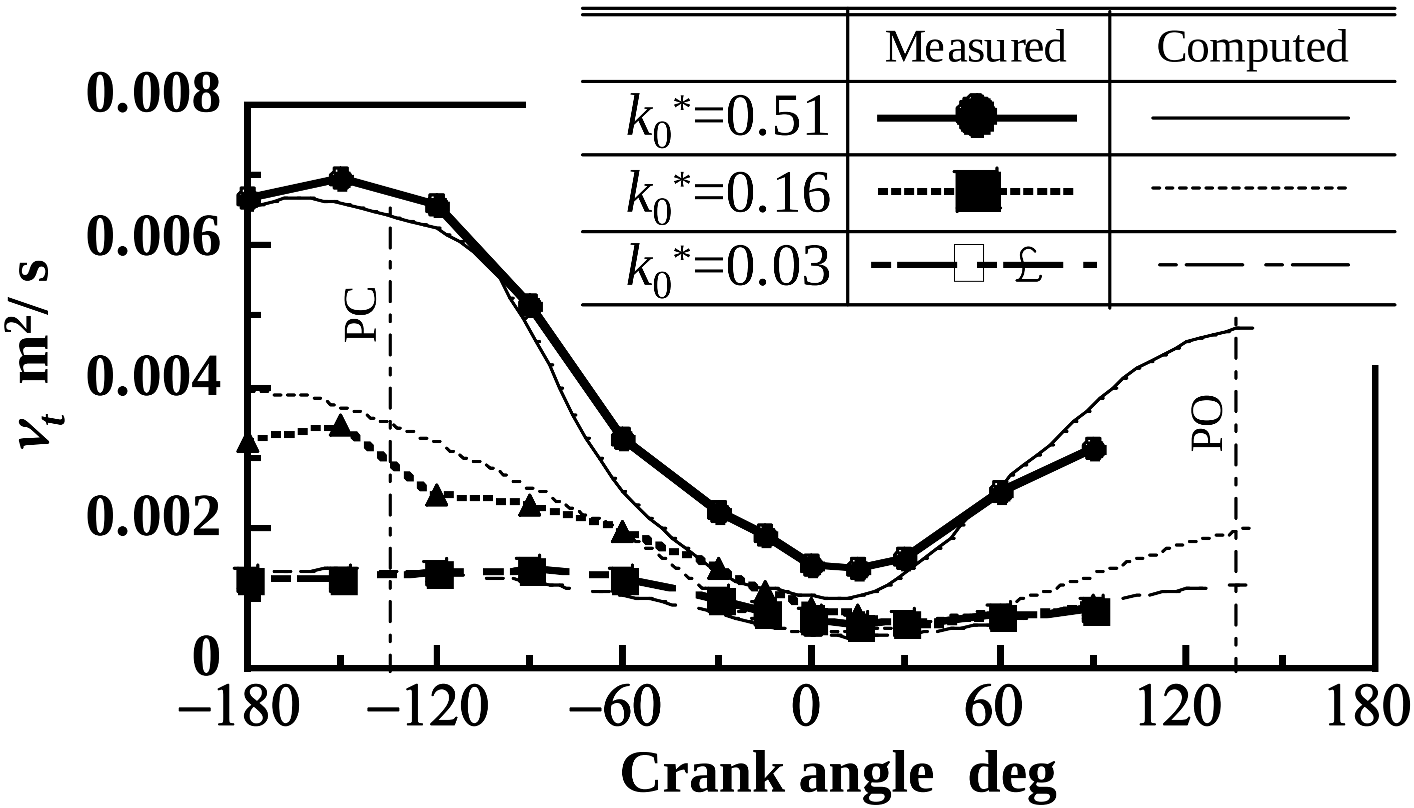


Measured and computed turbulence kinetic energies

Comparison of Integral Length Scale



Measured and computed integral length scales



Measured and computed turbulence kinematic viscosity

Conclusions

- Average rotation of a template in addition to average parallel movement improves the accuracy of integral length scale measurements when making cross-correlation of brightness of PIV image.

- Errors in measurement of integral length scale due to the limited range of wave length in PIV are estimated. The result shows that the errors are not considerable from a practical stand point.

- Measured and computed turbulence characteristics, including turbulence kinetic energy, integral length scale and turbulence kinematic viscosity, were compared for swirling turbulent flows in a rapid compression/expansion machine. The results show a good agreement and validate the dilatation effect.

Conclusions - cont’d

- The improved cross-correlation technique will be a better tool for providing turbulence characteristics in engine combustion chamber, in which compression/expansion is not always one-dimensional including compression of unburned gas during combustion.

Thank you for your attention