

Paradigm shift in modern flow measurement and gas flow metering

Y.Takeda* & Y.Murai**

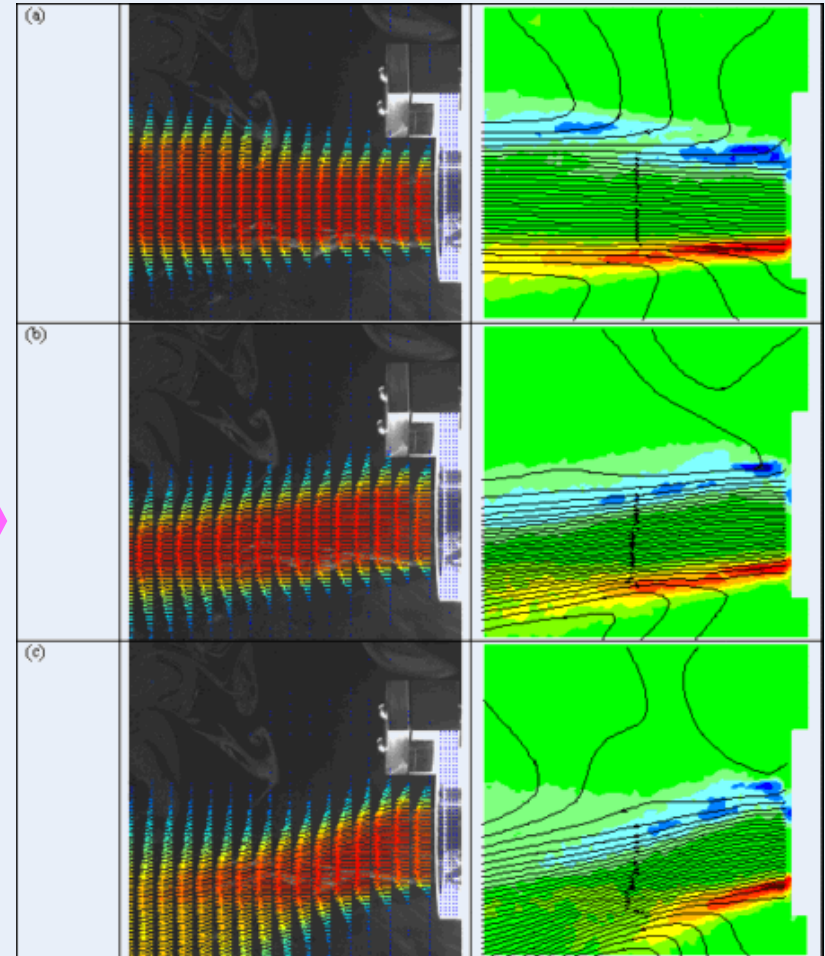
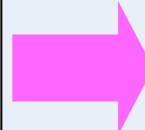
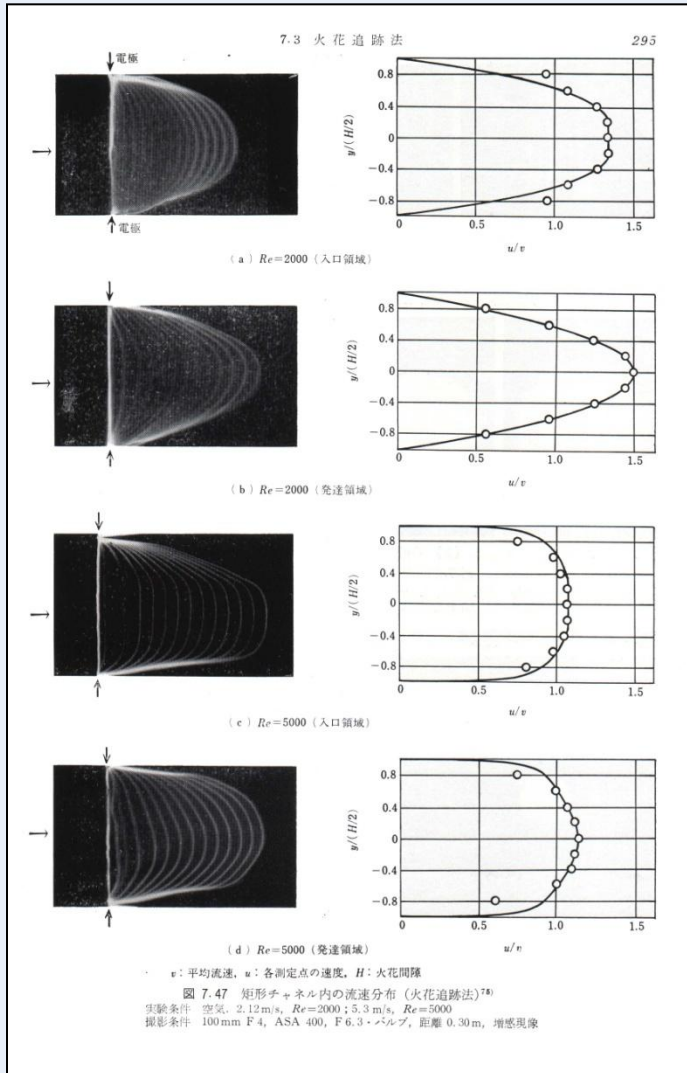
*** Tokyo Institute of Technology**

**** Hokkaido University**

Paradigm shift in modern flow measurement and gas flow metering

☆ Revolutionary change by
ultrasonic & laser applications

☆ **Back to the first principle**



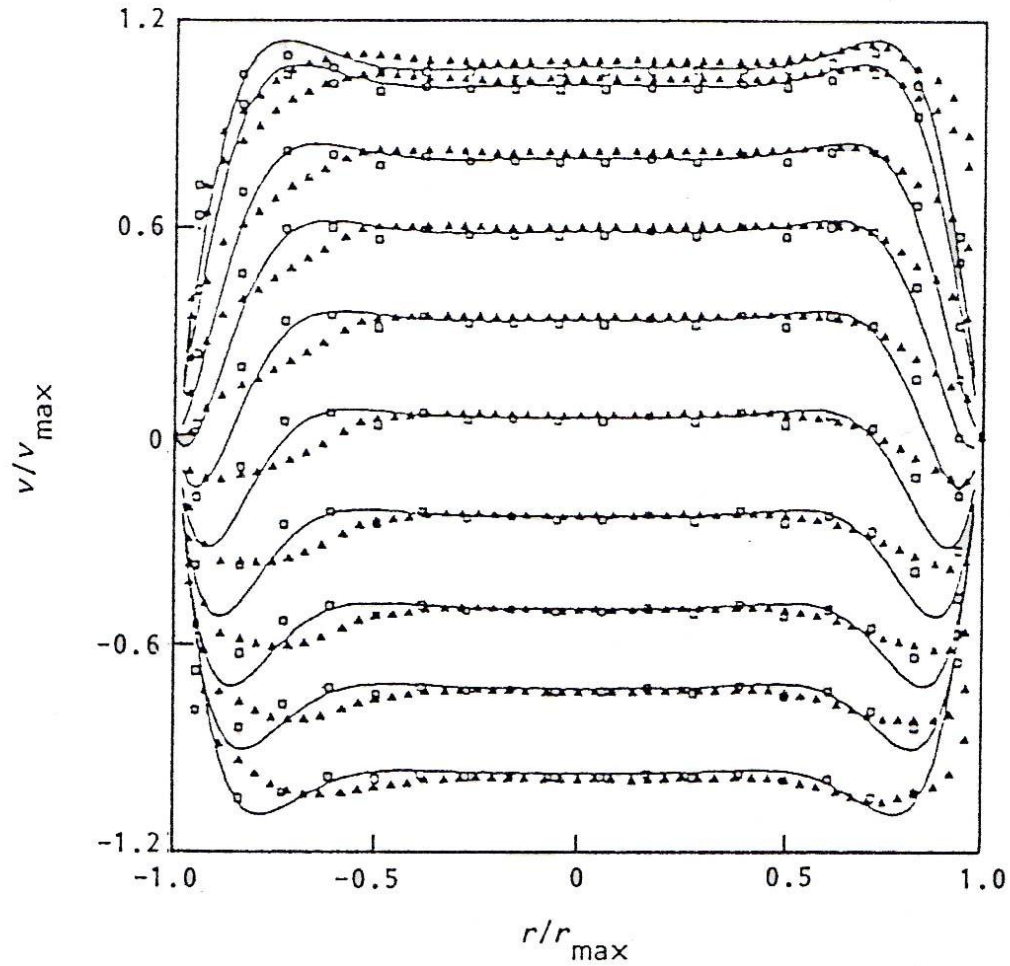


Figure 8 Comparison of LDV (□) and UVP (▲) measurements with theory (—)

Ultrasonic Doppler Method

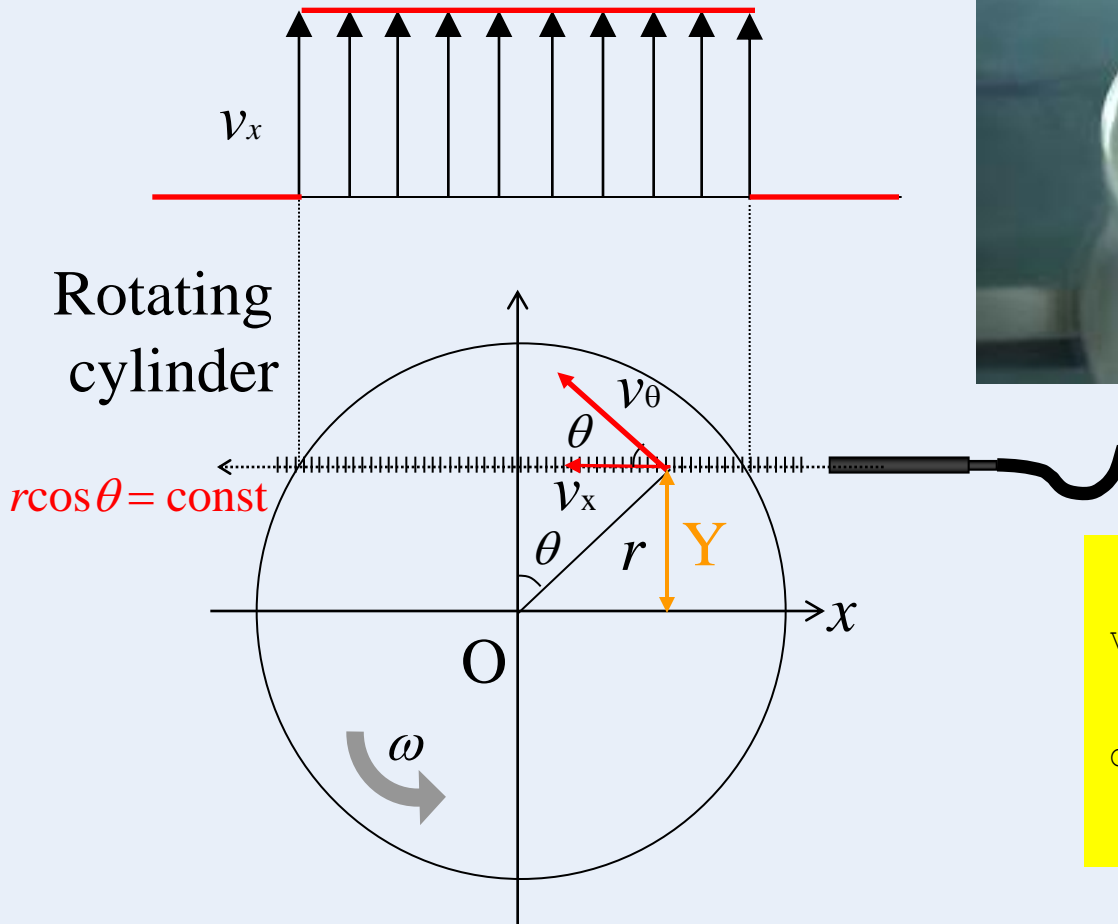
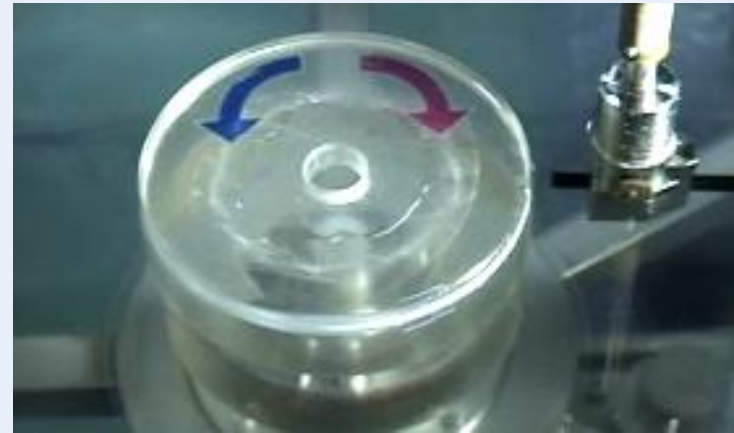
$u(x,t)$: One component on one spatial dimension

PIV : particle Identifying velocimetry

PTV : particle tracking velocimetry

$\vec{v}(\vec{x},t)$: Two components on two spatial dimension

Rotating Cylinder



$$v_\theta = r\omega$$

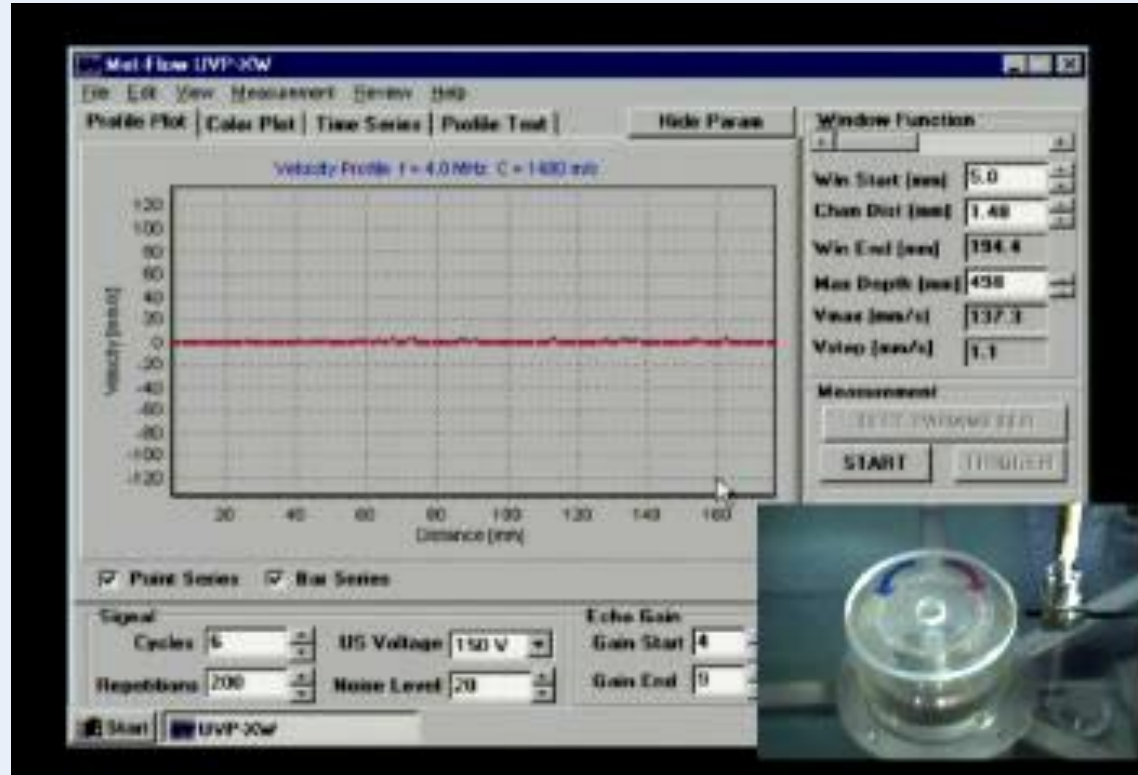
Velocity to be measured v_x

$$v_x = v_\theta \cos \theta = r\omega \cos \theta$$

On the line where $r \cos \theta = \text{const}$

$$v_x = Y\omega = \text{const}$$

Rotating Cylinder



UVP : Accuracy - Velocity and Position

Velocity profile in a rotating cylinder

Average velocity

Rotatio 52.32 sec
30 rotation

rps= 0.57339

Y= 111.00

Y0= 126.5

Averag -55.7

Vth= -55.84

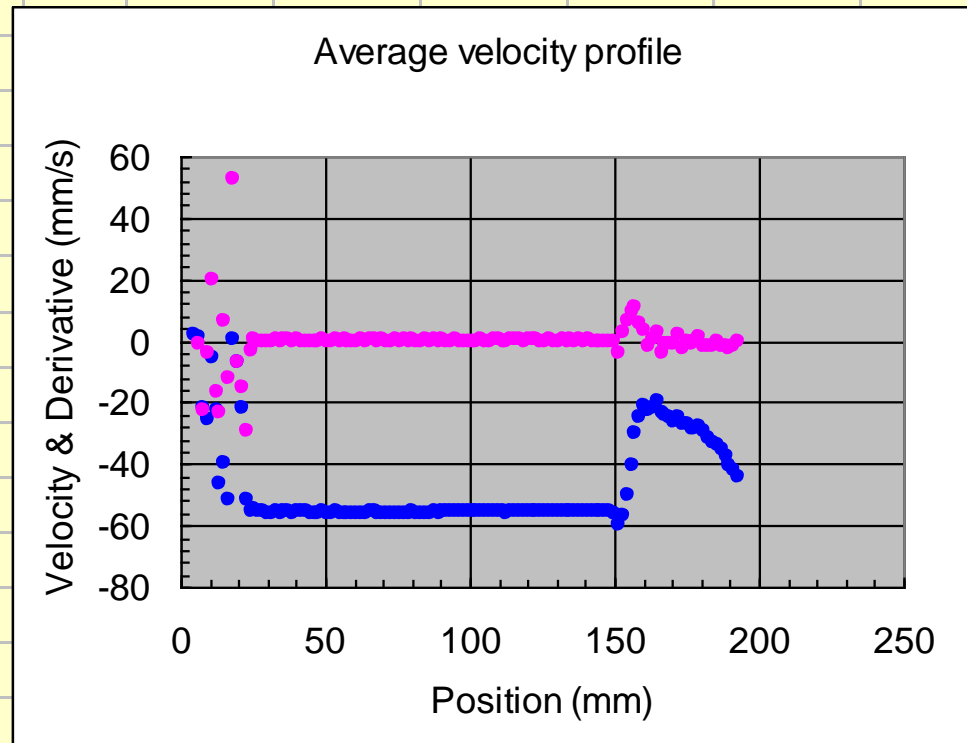
Diff= **0.3%**

Position

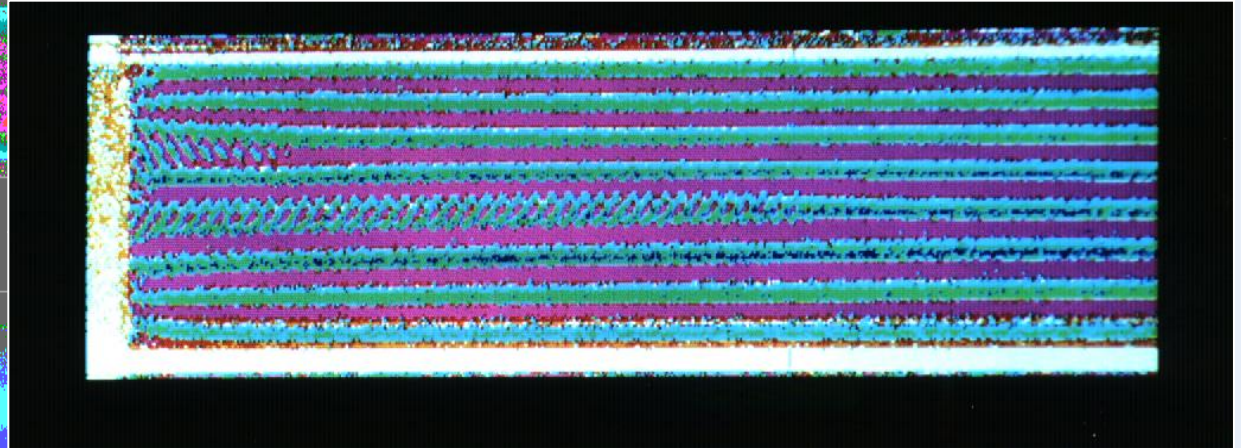
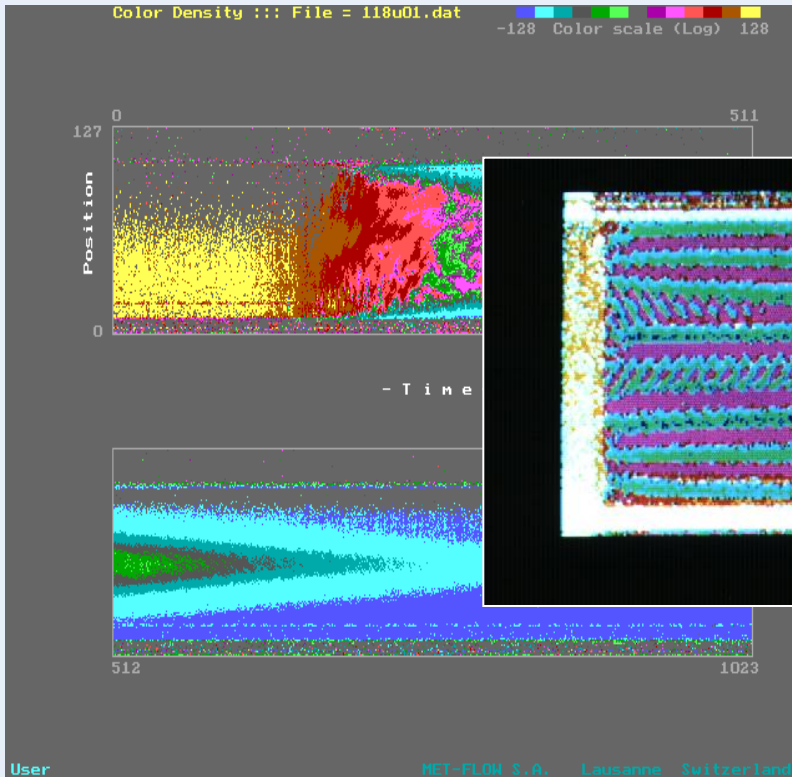
Pos. = 139.1 mm

Dtheo= 141.6 mm

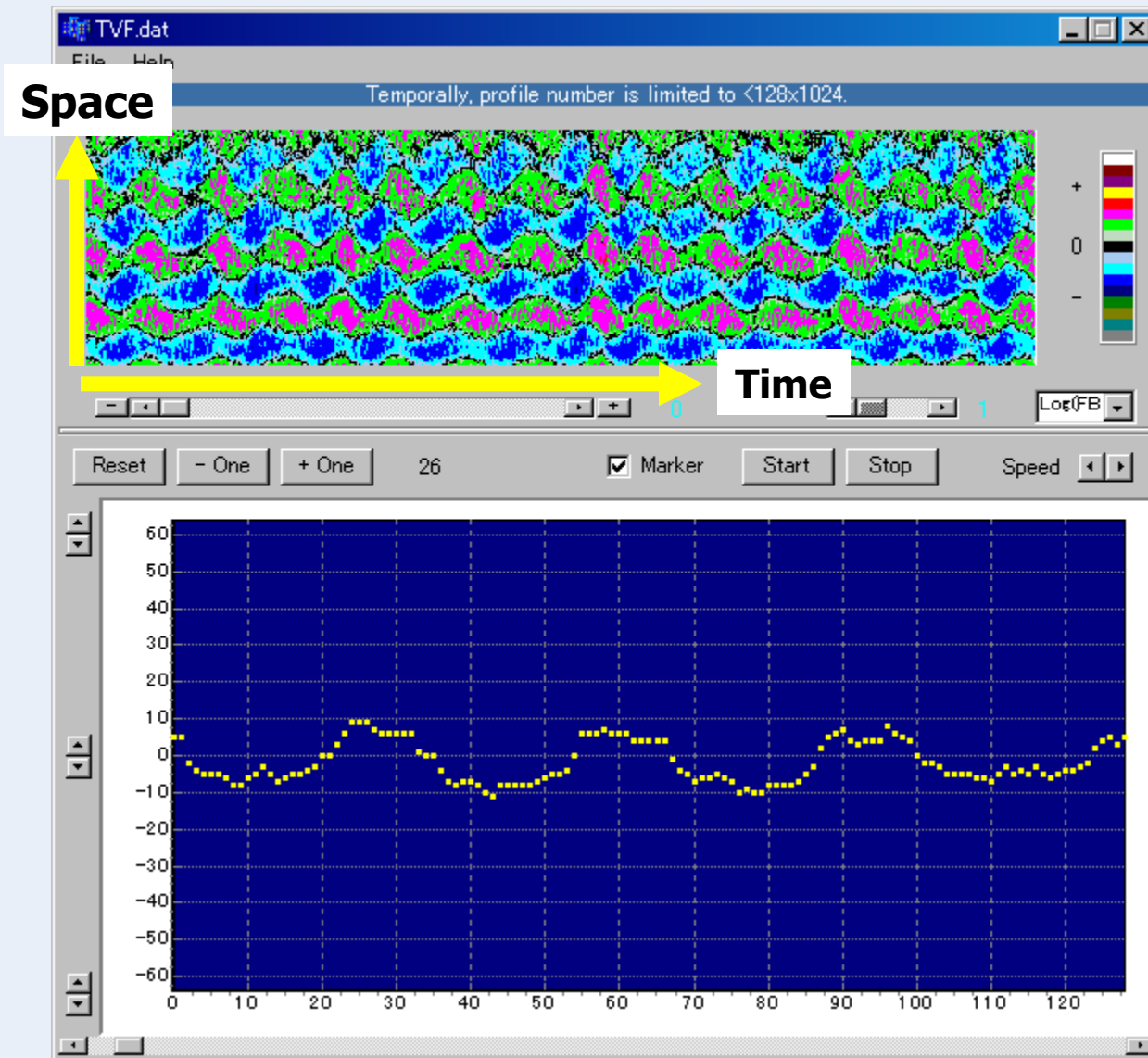
Diff = **1.8%**



Spatio-temporal velocity field

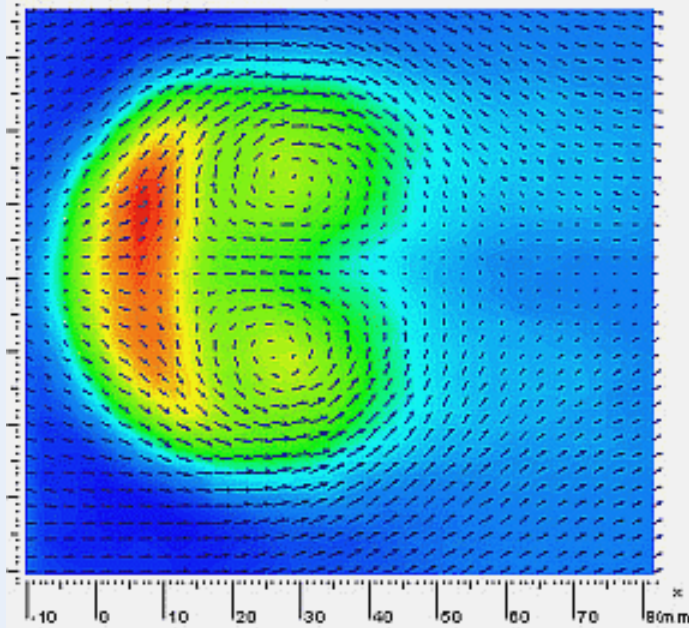


Spatio-temporal velocity field

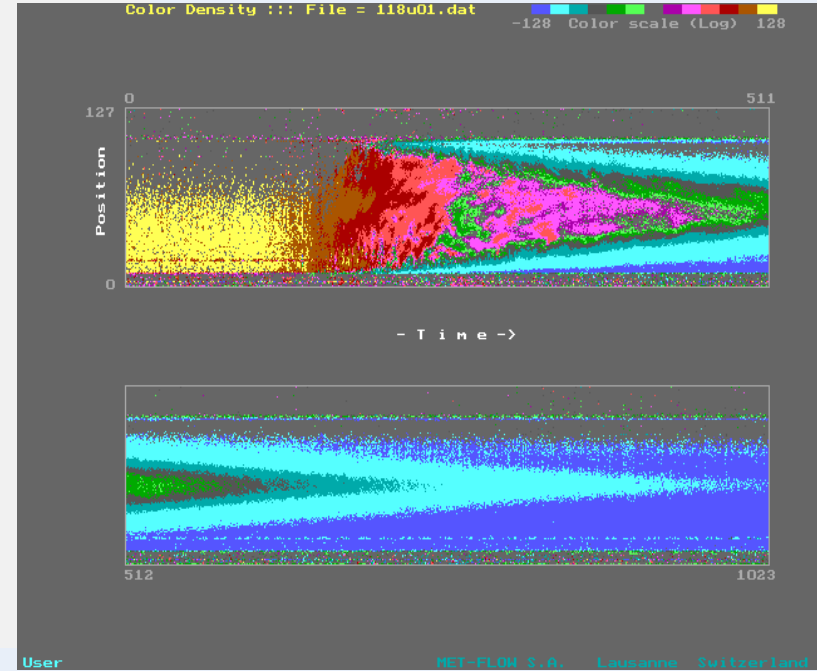


EFD → Measurement of flow field → $u(x, t)$

PIV(Laser)



UVP(ultrasound)



Advantages

- Space-time velocity field
- Opaque liquids
- Efficient flow mapping

Fluid dynamics

Liquid metal
Food

Fluid engineering

Flow metering

Ultrasonic Doppler Method

Advantages

- Space-time velocity field
- Opaque liquids
- Efficient flow mapping

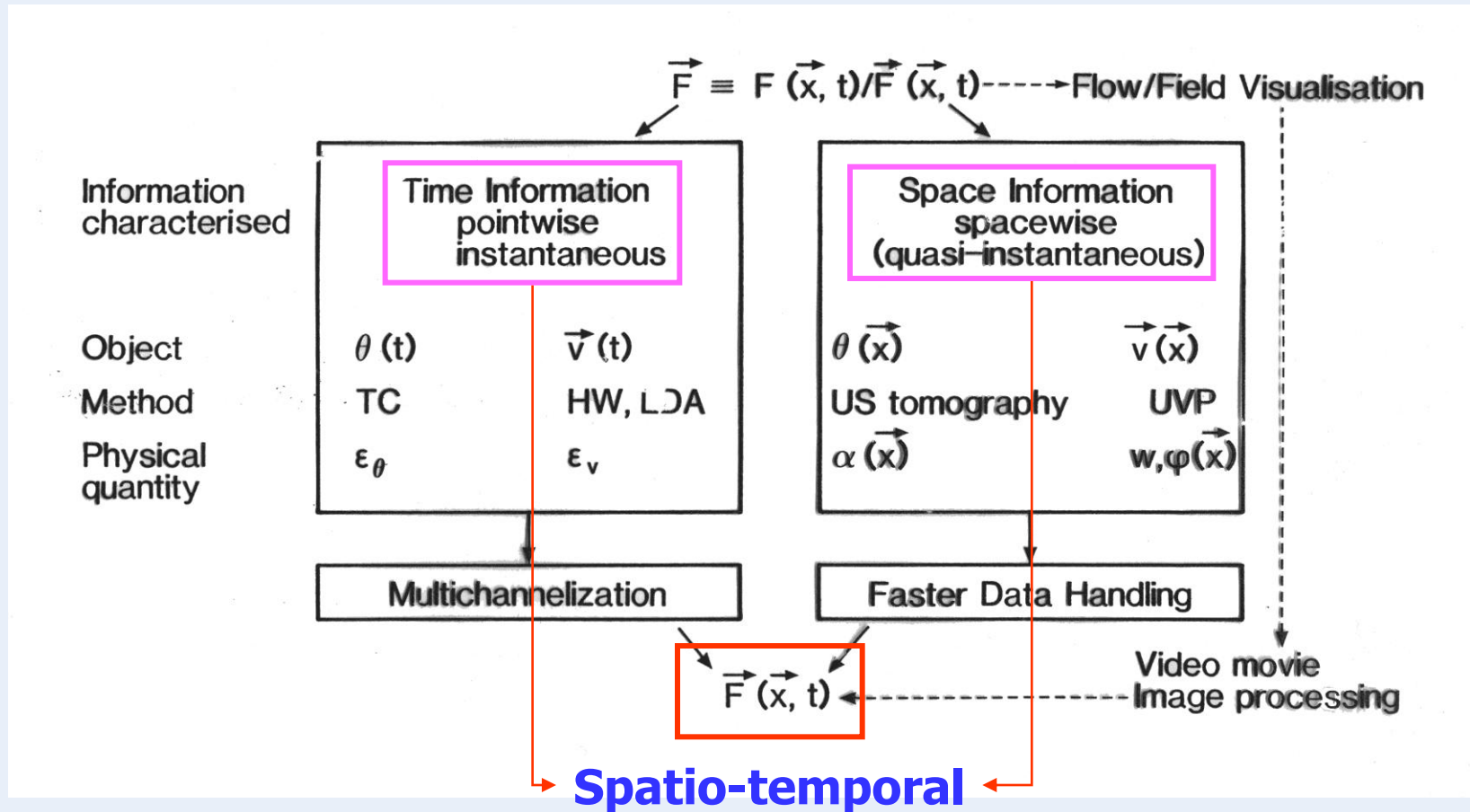
Fluid dynamics

Liquid metal
Food

Fluid engineering

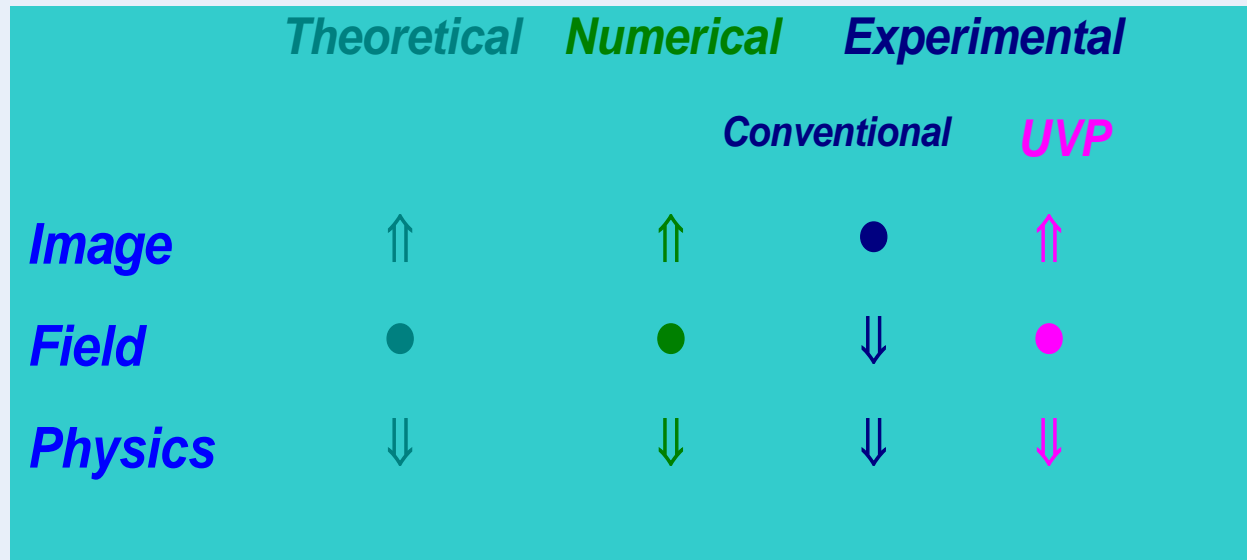
Flow metering

Paradigm shift



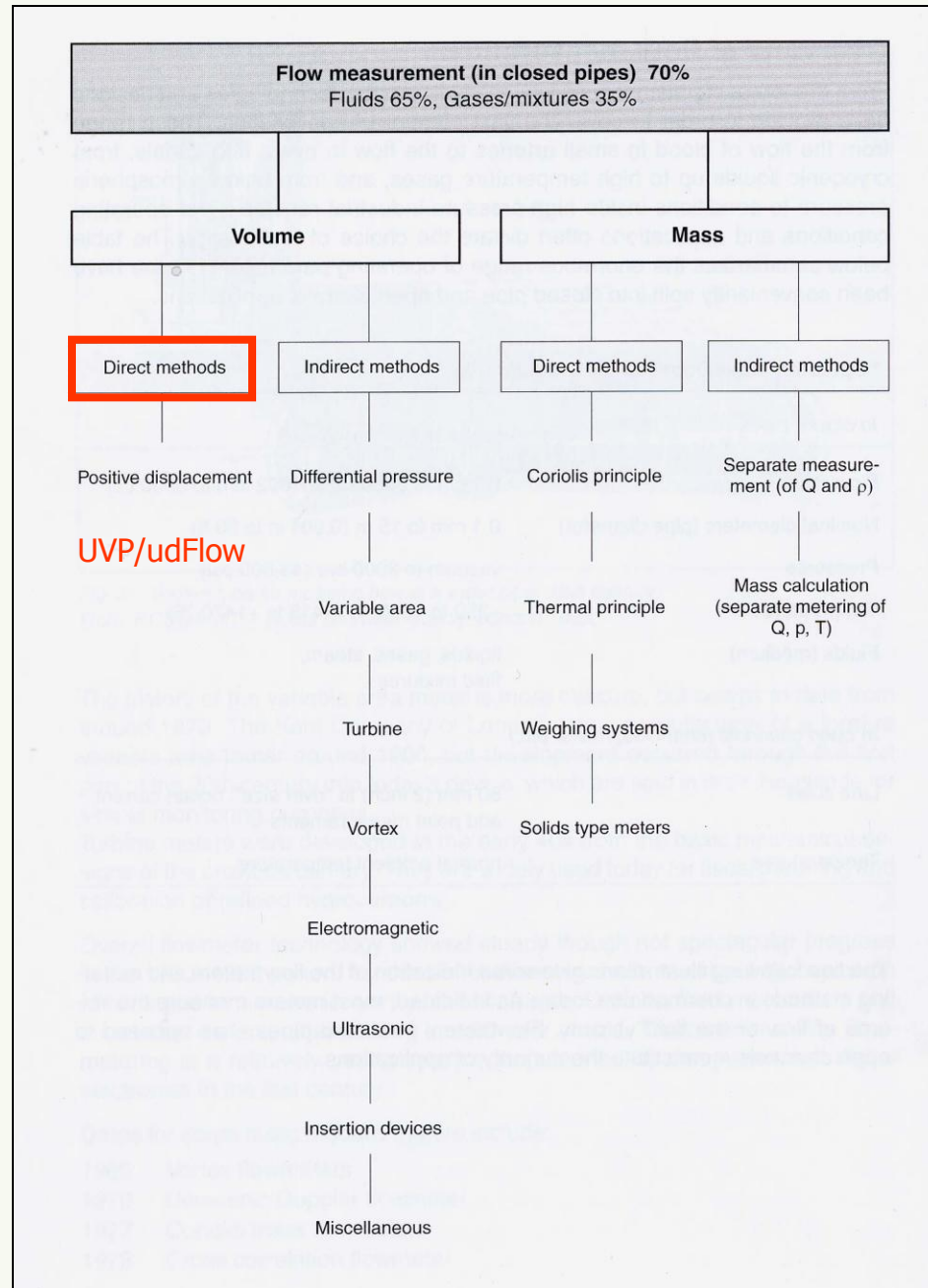
What physics can be made by UVP?

Methodology information flow in Fluid Mechanics



Flow metering

UVP - udFlow - DuoSonic



Paradigm shift in flow metering

1. 流量計開発の歴史

流量計開発のルーツを探ると、計測技術、Vol.31、No.12「流量計測の歴史－1. 古代オリエント－」で述べたように数千年前にナイル河の流量を水位計（ニロメータ）で計測したことに始まるとされている。また流量計測の概念は、古代ローマでヘロン（ギリシア、前130～75）が流量は「流速×流路の断面積」であると提案し、ローマ水道の1日の送水量を99万 m^3 と計算したことに始まったとされている。しかし流速をどうやって計測したかは、筆者の調べた範囲では定かではない。

First principle

$$m = \rho \int \mathbf{v}(\mathbf{x}, t) \cdot d\mathbf{A}$$

$$\mathbf{v}(\mathbf{x}, t) : 3C3D$$

$$(V_x, V_y, V_z) \\ (x, y, z)$$

Flow rate

$$m = \rho \int \mathbf{v}(\mathbf{x}, t) \cdot d\mathbf{A}$$

$\mathbf{v}(\mathbf{x}, t) : 3C3D$

(V_x, V_y, V_z)
 (x, y, z)

Flow rate measurement Theoretical in conduit (pipe)

$$m/\rho = \iint v_z(r, \theta, t) r dr d\theta$$

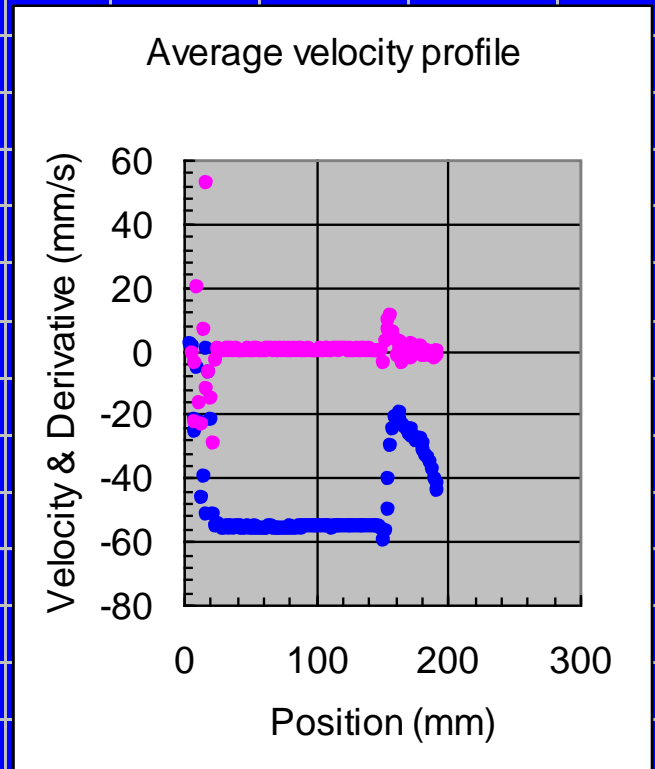
$$\approx (\pi/N) \sum_i \left\{ \int v_z(r, \theta_i, t) r dr \right\}$$

*Measuring lines (i) are diameters
at different angles.*

Principles

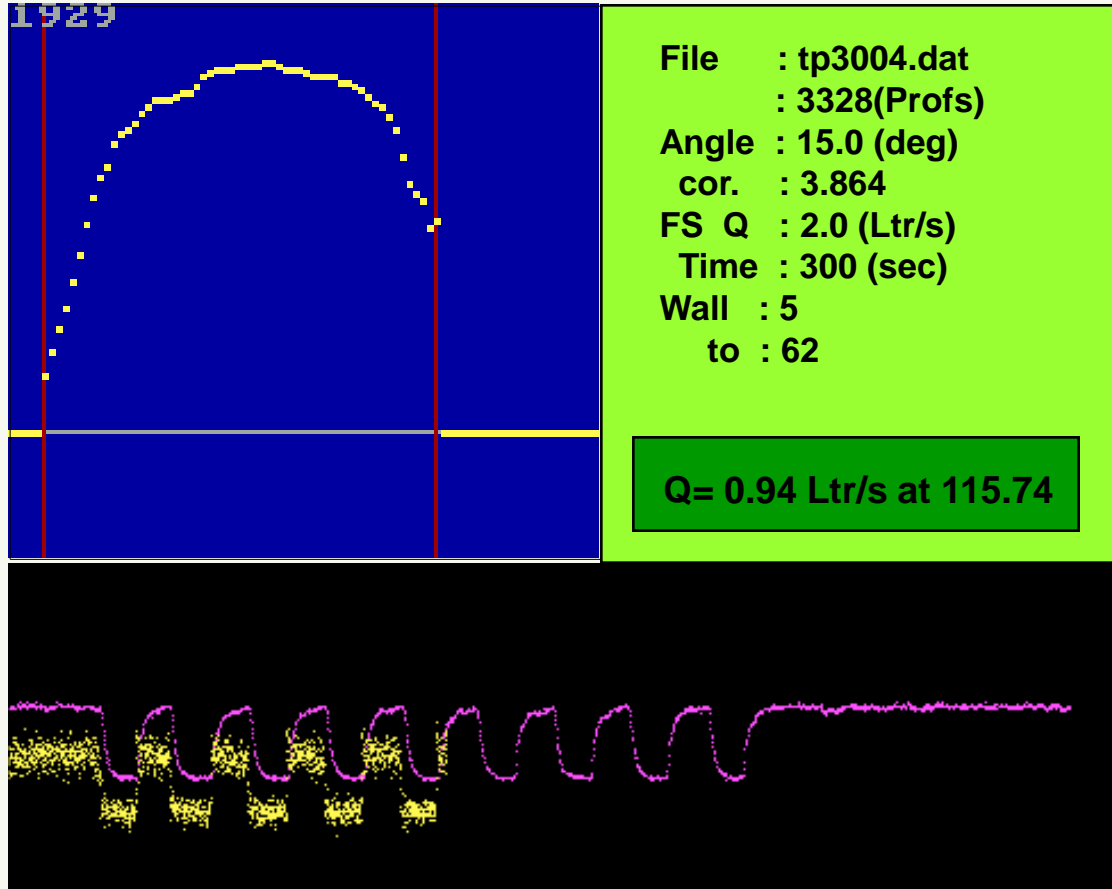
- Ultrasonic
- UVP
- udFlow

Average velocity	
Rotatio	52.32 sec
	30 rotation
rps=	0.57339
Y=	111.00
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Averag	-55.7
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Diff=	0.3%
Position	
Pos. =	139.1 mm
Dtheo=	141.6 mm
Diff =	1.8%

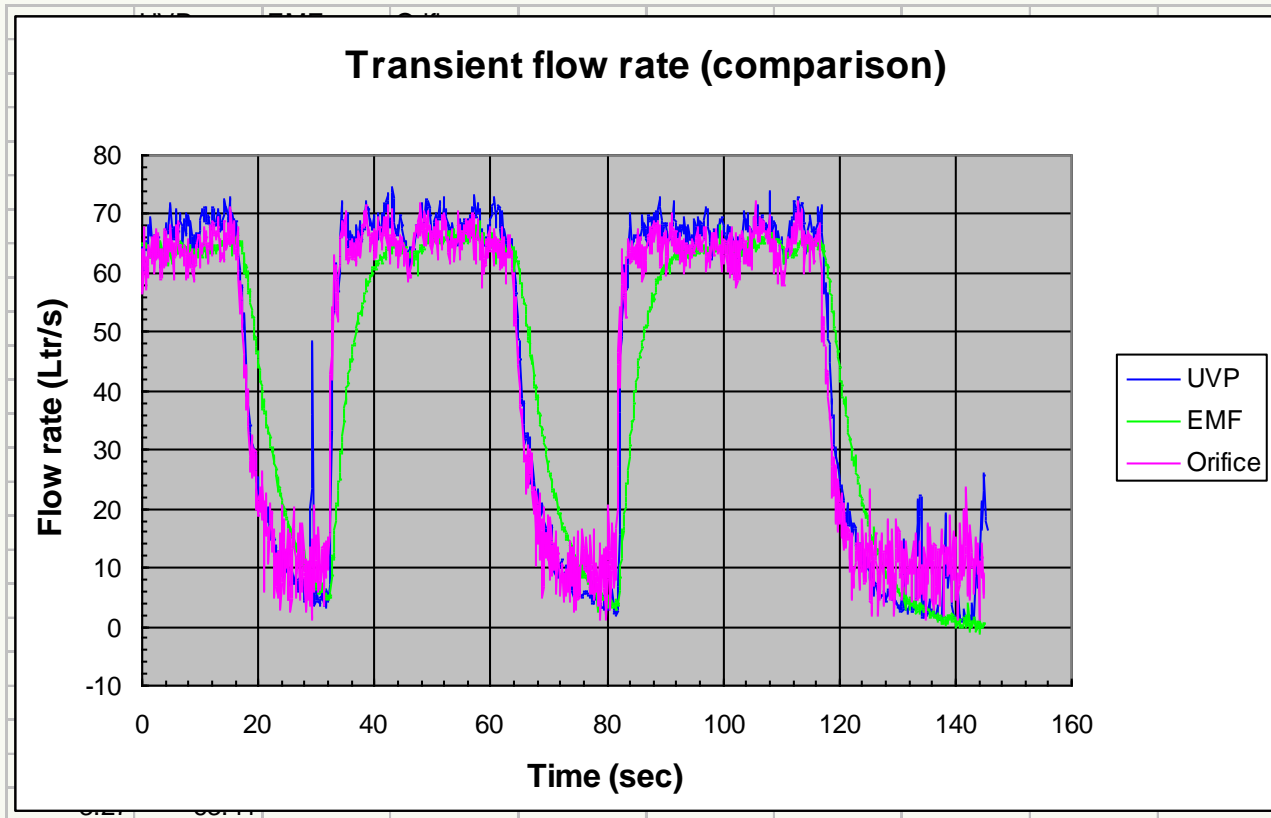


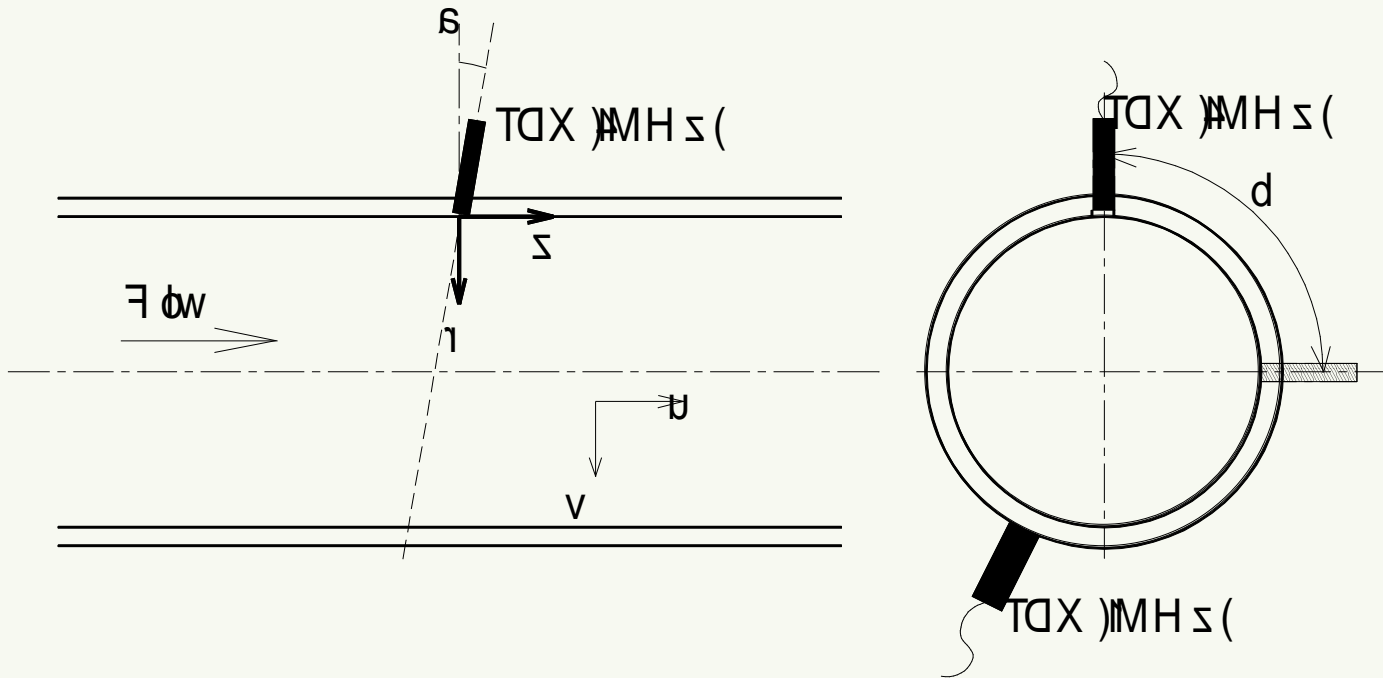
Small pipe

Profile and flow rate

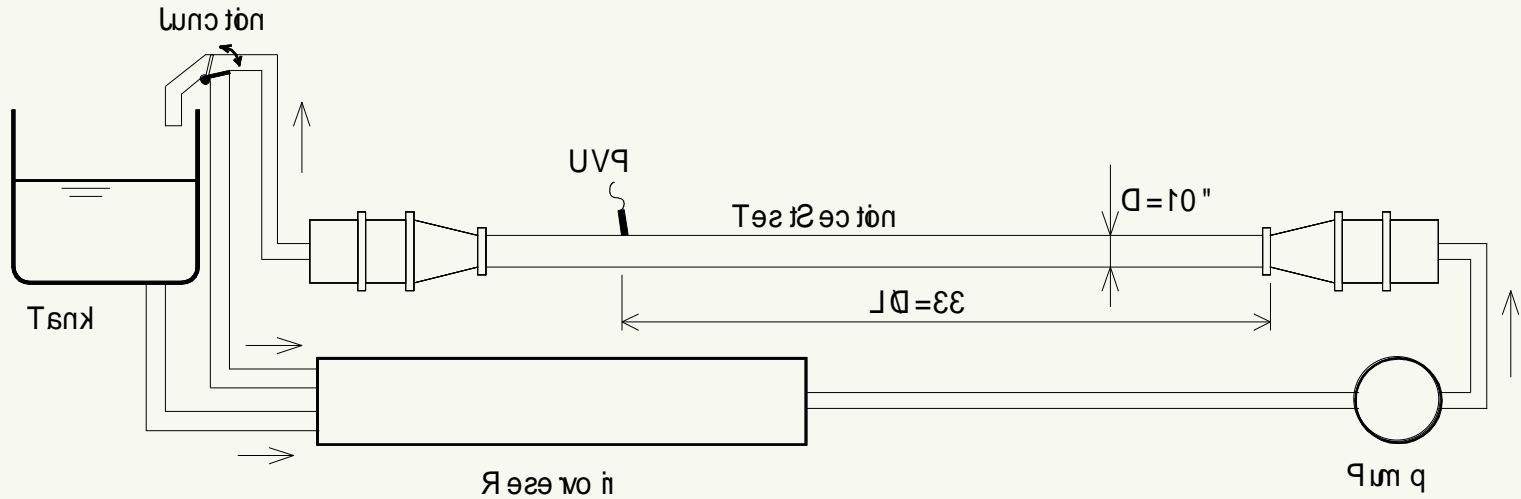


Flow rate measurement using UVP

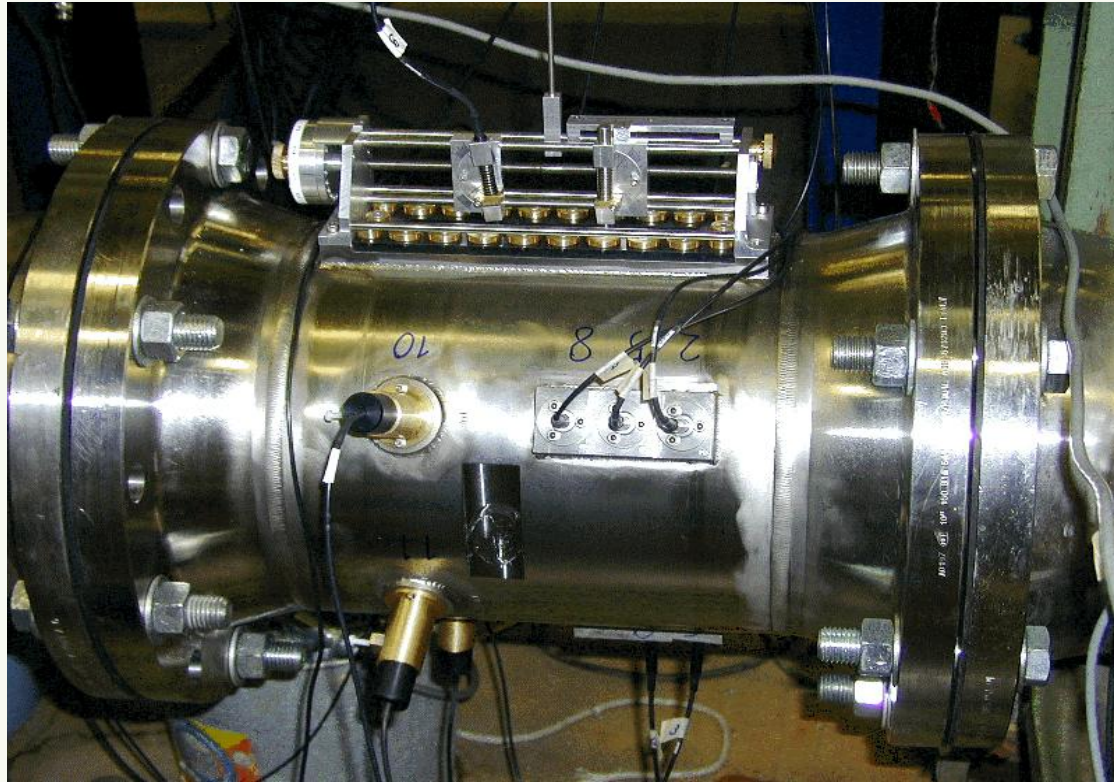




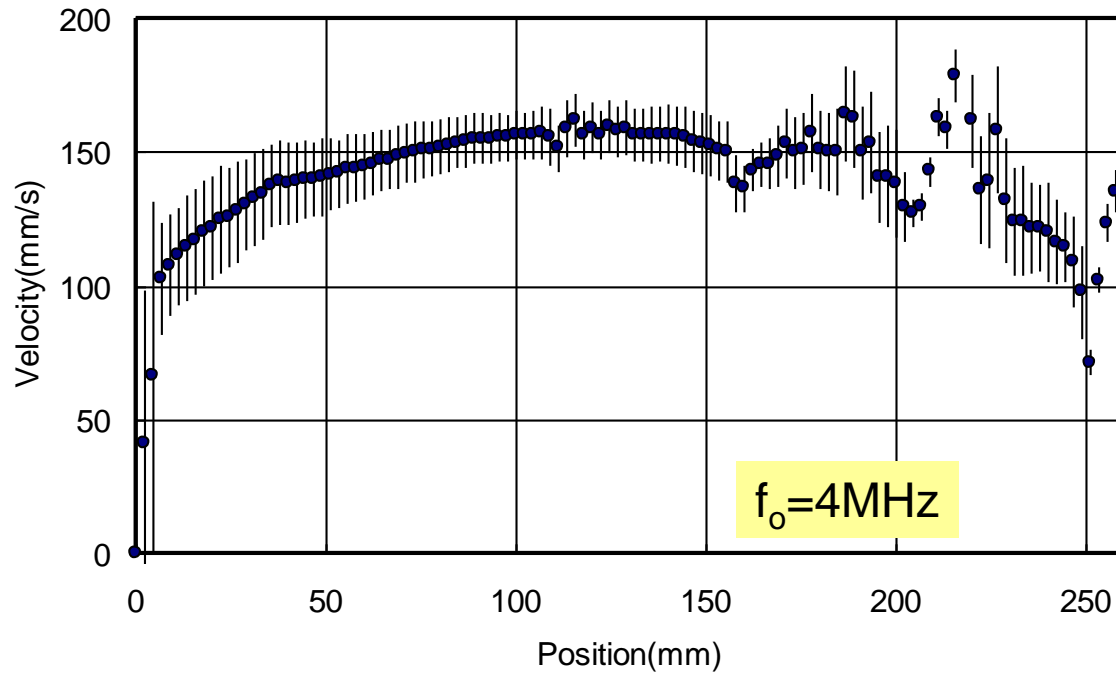
Test section detail and coordinate system



Schematic of the experimental apparatus
 - NIST standard calibration system -

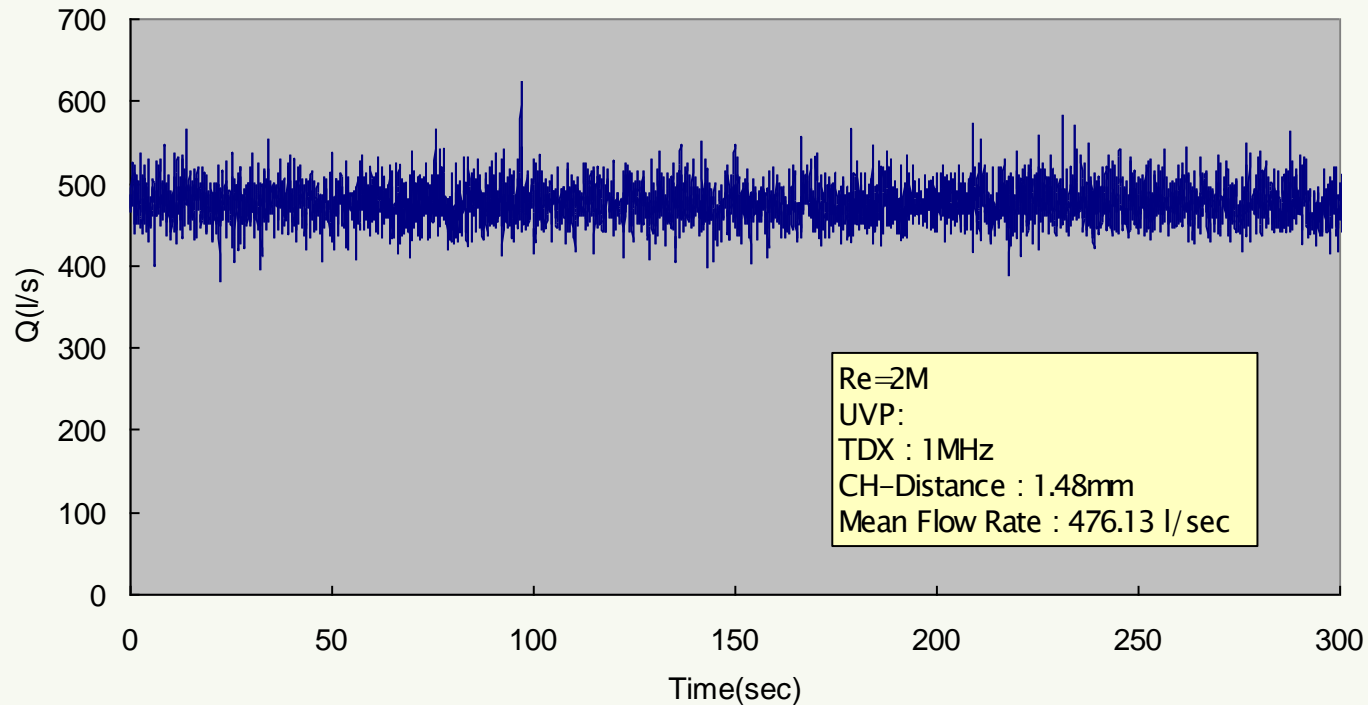


Picture of test section



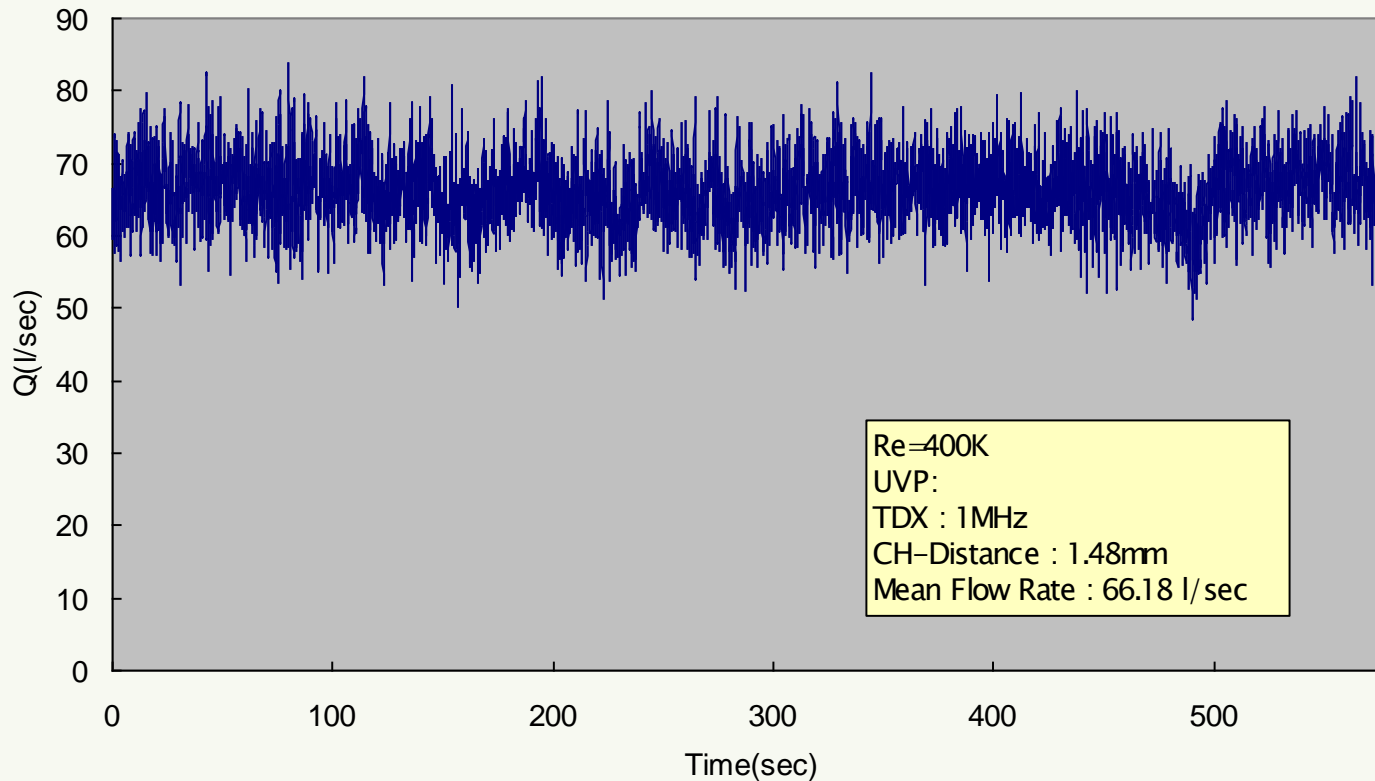
Mean velocity profile ($Re=400K$)

PSI-TEPCO-NIST(14,MAY,1999) data:N1037.dat



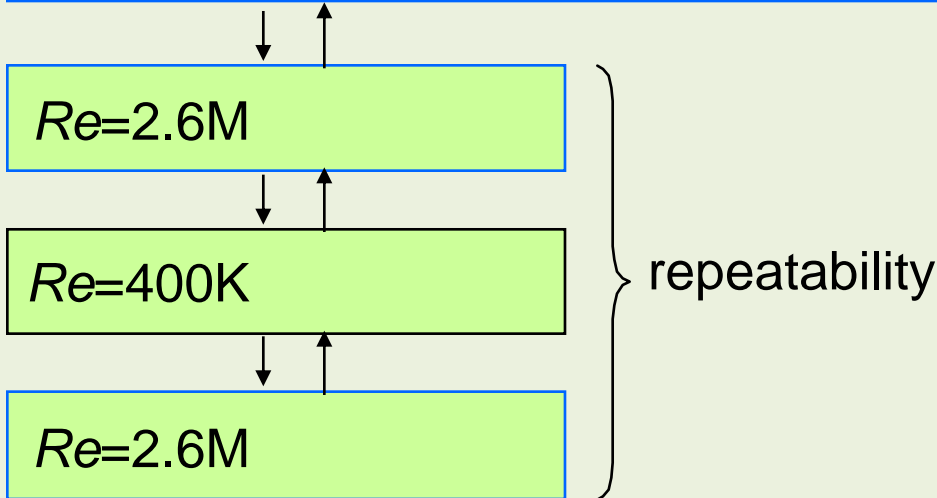
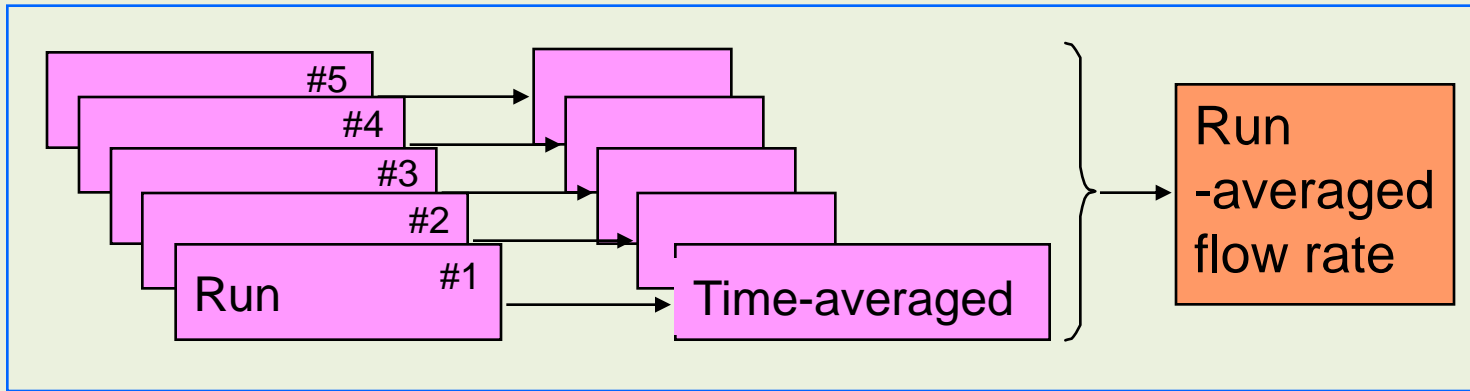
Transient flow rate ($Re=2M$)

PSI-TEPCO-NIST(14,MAY,1999) data:N1025.dat



Transient flow rate ($Re=400K$)

$Re=400K$



Experimental procedure

- NIST standard calibration system -

Flow Measurement

- Comparison with Weight Measurement -

Re=400K
fo=4MHz

	File	UVP (L/s)		Weight Re=400k		Difference	% error
		Average	Deviation	GPM	L/s		
N190599A	N0324.dat	70.60	3.25	1109.14	69.97	-0.63	-0.90%
	N0325.dat	70.24	3.22	1110.27	70.04	-0.20	-0.29%
	N0326.dat	70.76	3.01	1110.30	70.04	-0.72	-1.03%
	N0327.dat	70.61	3.00	1110.23	70.04	-0.57	-0.82%
	N0328.dat	70.23	3.12	1110.78	70.07	-0.16	-0.23%
N190599B	N0329.dat	70.20	3.31	1110.87	70.08	-0.12	-0.17%
	N0330.dat	70.36	3.41	1111.42	70.11	-0.25	-0.35%
	N0331.dat	70.20	3.39	1110.32	70.04	-0.15	-0.22%
	N0332.dat	69.86	3.56	1109.81	70.01	0.15	0.21%
	N0333.dat	69.90	3.38	1110.72	70.07	0.17	0.24%
N200599A	N0336.dat	70.21	3.17	1113.62	70.25	0.04	0.05%
	N0337.dat	70.34	3.17	1113.76	70.26	-0.08	-0.11%
	N0338.dat	70.38	3.39	1113.61	70.25	-0.13	-0.19%
	N0339.dat	70.30	3.40	1115.04	70.34	0.04	0.06%
	N0340.dat	70.16	3.41	1114.10	70.28	0.12	0.17%
N200599B	N0345.dat	69.81	3.22	1111.90	70.14	0.33	0.48%
	N0346.dat	70.12	3.12	1113.85	70.27	0.15	0.21%
	N0347.dat	69.67	3.25	1113.00	70.21	0.54	0.77%
	N0348.dat	69.88	3.21	1112.82	70.20	0.32	0.45%
	N0349.dat	70.07	3.29	1113.73	70.26	0.19	0.27%
N200599D	N0350.dat	70.20	3.29	1101.77	69.50	-0.70	-1.00%
	N0351.dat	69.97	3.20	1102.62	69.56	-0.41	-0.59%
	N0352.dat	70.13	3.35	1102.90	69.57	-0.56	-0.80%
	N0353.dat	70.11	3.31	1102.85	69.57	-0.54	-0.78%
	N0354.dat	70.36	3.38	1103.20	69.59	-0.77	-1.10%
N200599E	N0355.dat	69.76	2.96	1103.30	69.60	-0.16	-0.23%
	N0356.dat	69.67	3.19	1103.51	69.61	-0.06	-0.08%
	N0357.dat	69.72	3.23	1103.49	69.61	-0.11	-0.16%
	N0358.dat	69.44	3.15	1103.65	69.62	0.18	0.26%
	N0359.dat	69.57	3.22	1103.44	69.61	0.04	0.06%
N200599F	N0373.dat	69.96	3.07	1101.77	69.50	-0.46	-0.66%
	N0374.dat	69.70	3.21	1102.62	69.56	-0.14	-0.20%
	N0375.dat	69.36	3.24	1102.90	69.57	0.22	0.31%
	N0376.dat	69.54	3.13	1102.85	69.57	0.03	0.05%
	N0377.dat	69.71	3.22	1103.20	69.59	-0.12	-0.17%
	Average	70.03	0.13	1108.10	69.90	-0.13	-0.18%

High precision flowmeter

Better than 1%



Water



Starch



Milk



Orange juice

e-Front runners

For liquids

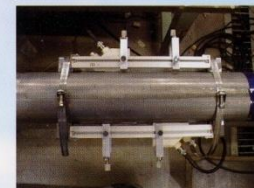
高精度ハイブリッド超音波流量計

新方式のパルスドップラー式と伝搬時間差式を併用した
新しい概念の超音波流量計 (非接触測定)



変換器 (FSH)

Duosonics

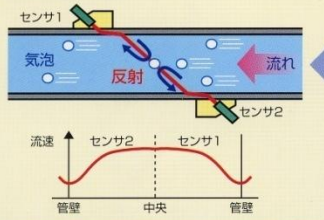


検出器 (FSW) 設置例

原理・構成

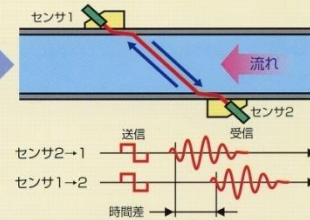
パルスドップラー式

- 超音波パルスを液体中へ送信し、液体中の気泡やパーティクル等の反射体からエコーのドップラー周波数が流速で変化することを利用して流速分布を求め流量を測定
- 不透明な液体に向く



伝搬時間差式

- 上流側と下流側から斜めに超音波パルスを伝搬させ、流れにより生ずる時間差を検出して流量を測定
- 清浄な液体に向く



流体の状態に応じて自動切換測定

特長

- 超音波の反射と透過を用いる両方式の自動切換により、気泡やパーティクルによらず広範な液体の流量測定が可能
- 0.5~1%の高精度測定
- 流速分布のリアルタイム測定 (パルスドップラー式) → 補正係数が不要、直管条件を緩和、未発達流へ適用可
- 高速応答 0.1s (ドップラー式) / 0.5s (伝搬時間差式)

用途

原油、排水、染料、繊維入り飲料水、ドレッシング、豆乳、ヨーグルト、スラリー流体など従来測定困難だった流体の流量測定が可能となりました。

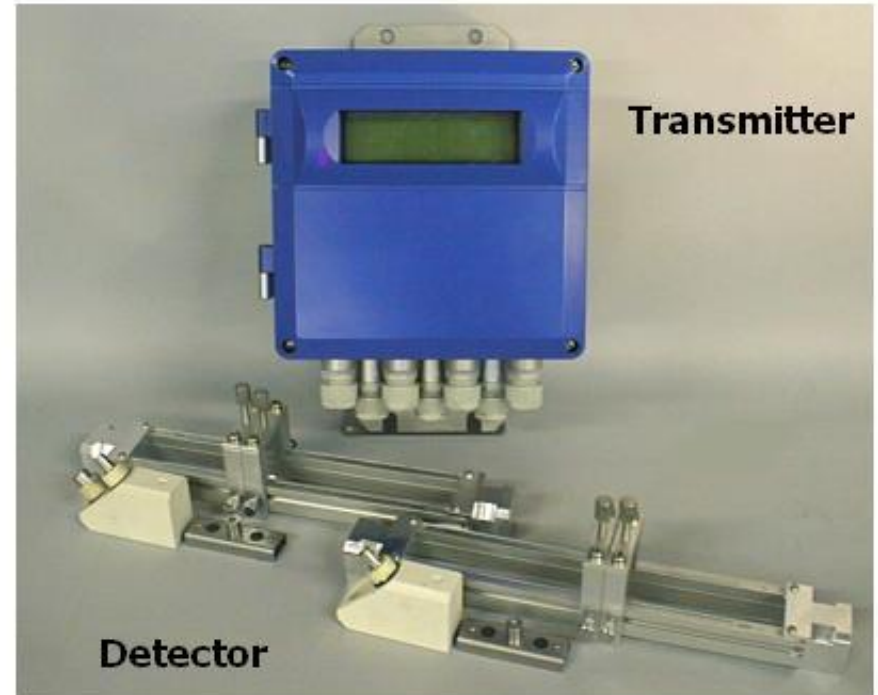


PCによる流速分布測定

富士電機システムズ株式会社

Hybrid Ultrasonic Flow Meter

- The world's first Hybrid Ultrasonic Flow Meter combining pulse-Doppler method with transit time method
- Real time measurement of velocity profiles in case of pulse-Doppler
- Non-intrusive flow measurement
- Provided by *Fuji Electric Systems Co., Ltd.*



Flow metering

Circular pipe

Principle

$$Q(t) = \iint V_z(r, \theta, t) r dr d\theta$$

- High accuracy
- Transient flow rate

2007.5.27 NEDO研究成果報告会

Multiphase Flow meter

Development of real time measurement of componentwise flowrate on multiphase flow pipe line

Y.Murai, Y.Takeda, Y.Tasaka

Graduate School of Engineering, Hokkaido University

本課題の混相流量計の基本的概念

流動様式を拘束しない



流動抵抗を与えない

実地ラインでそのまま計測

任意の流動様式に適用可能

不確かな物理モデルを使わない



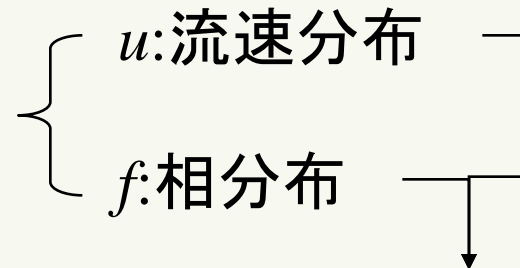
キャリブレーションが不必要

計測対象範囲が広い

多様性に富む混相流に有利

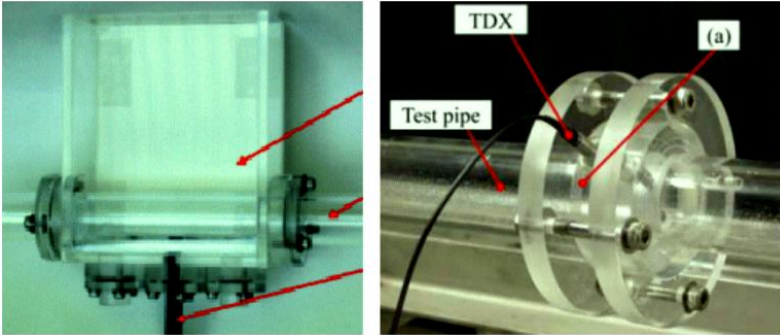
第一原理による計測

$$Q = \int_A f u dA$$

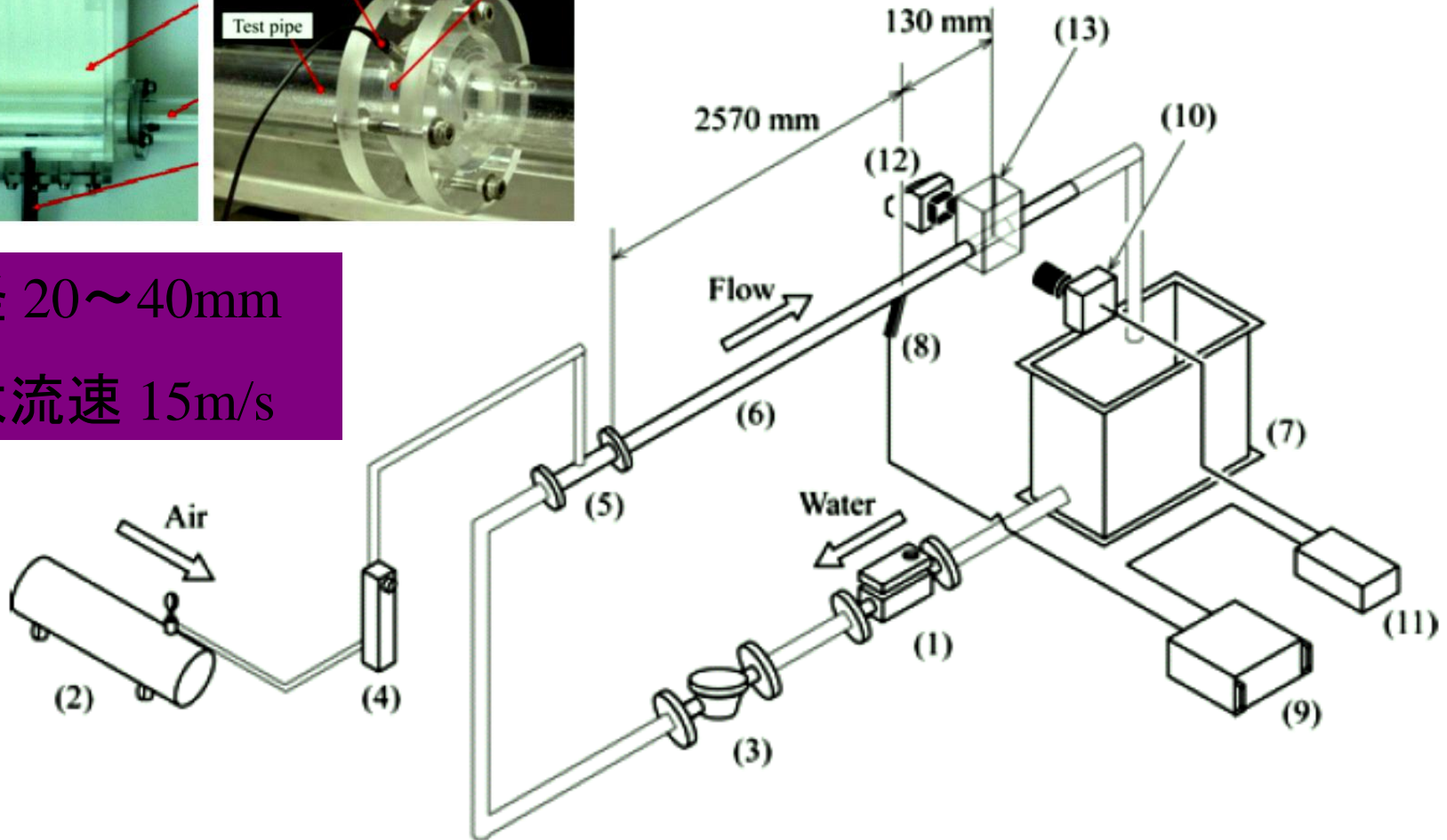


超音波ドップラー流速分布計

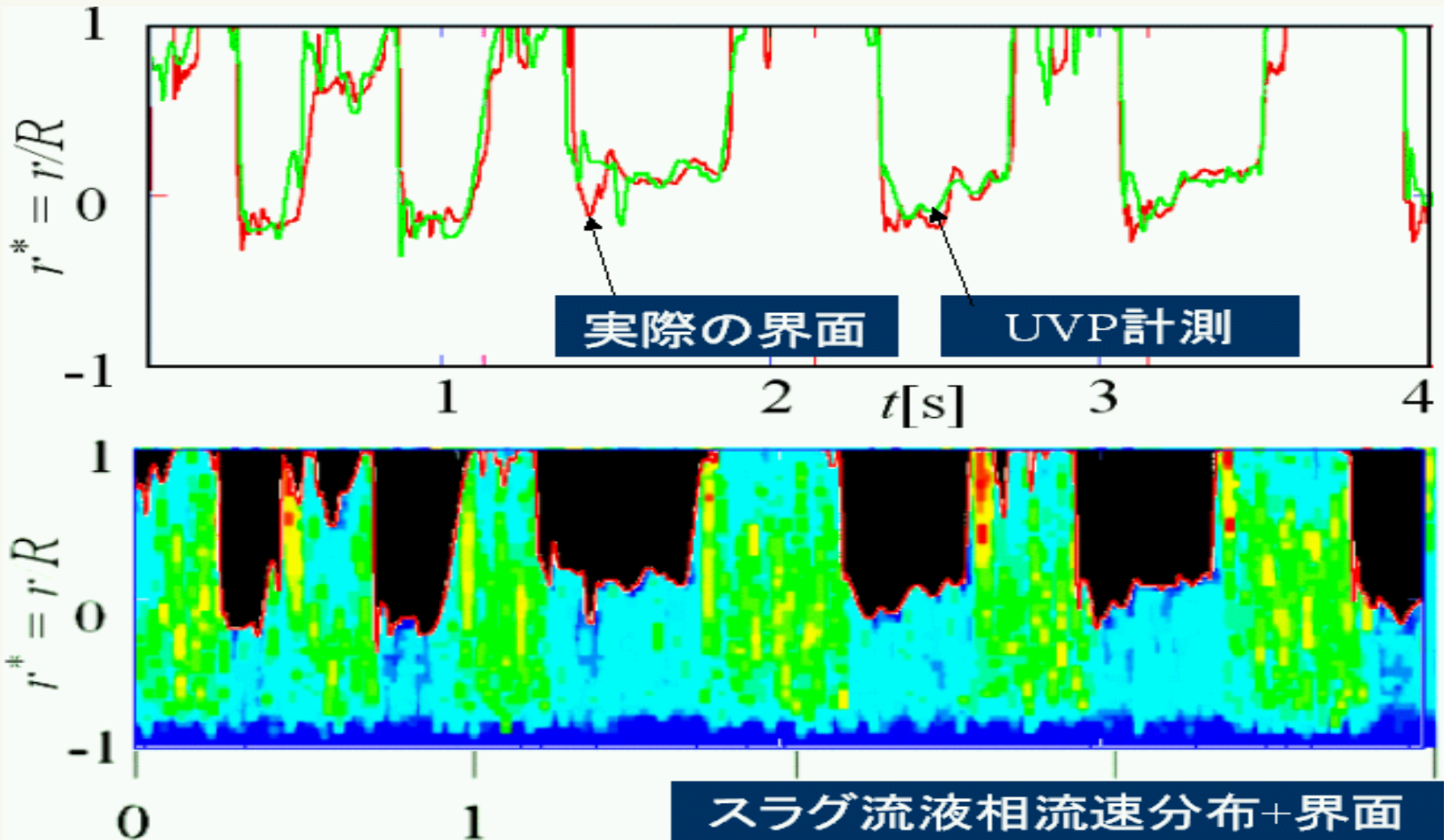
パイプライン用としての気液管内流実験装置



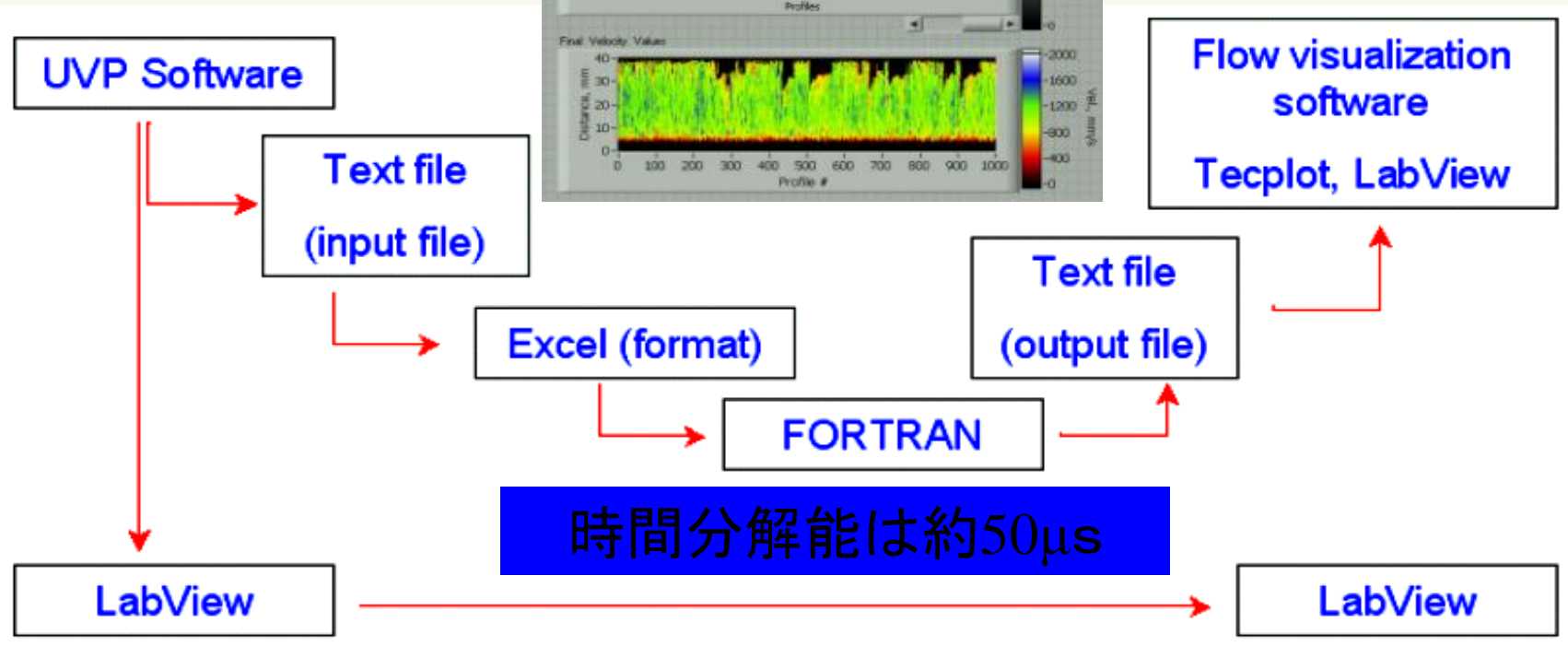
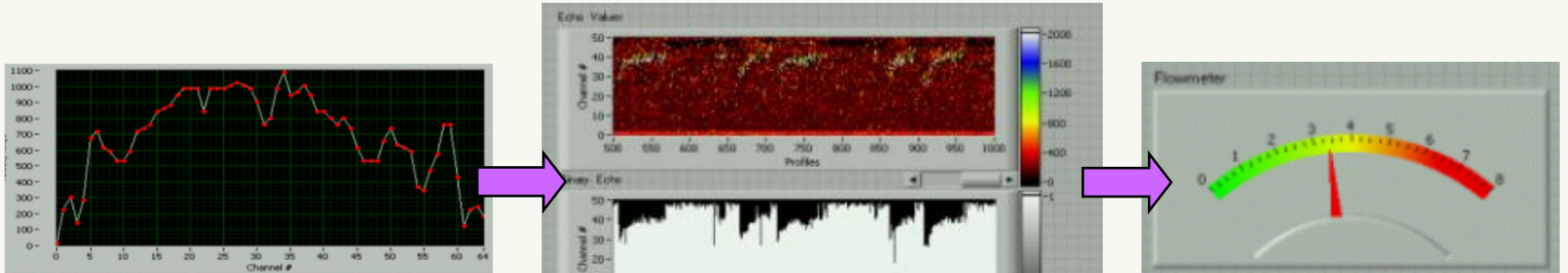
口径 20~40mm
最大流速 15m/s



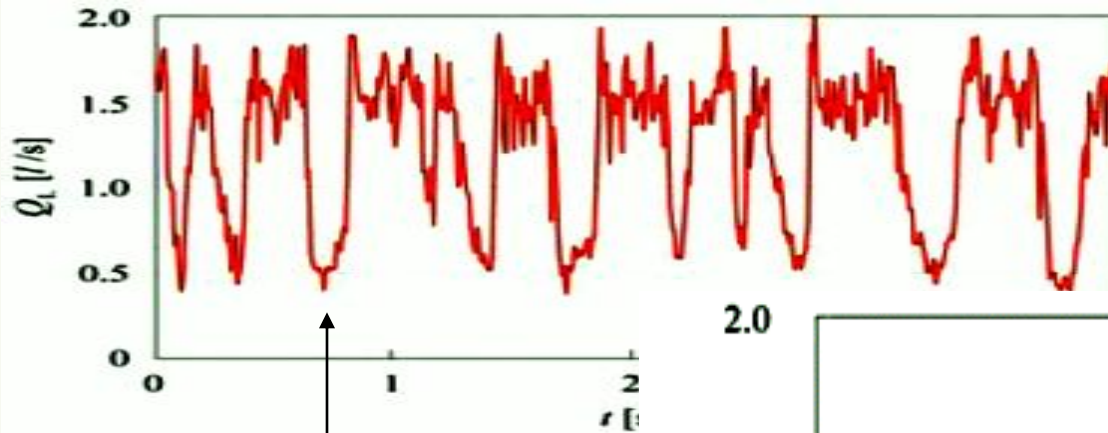
超音波と光による界面計測精度の照合



リアルタイム計測モニタリングシステム



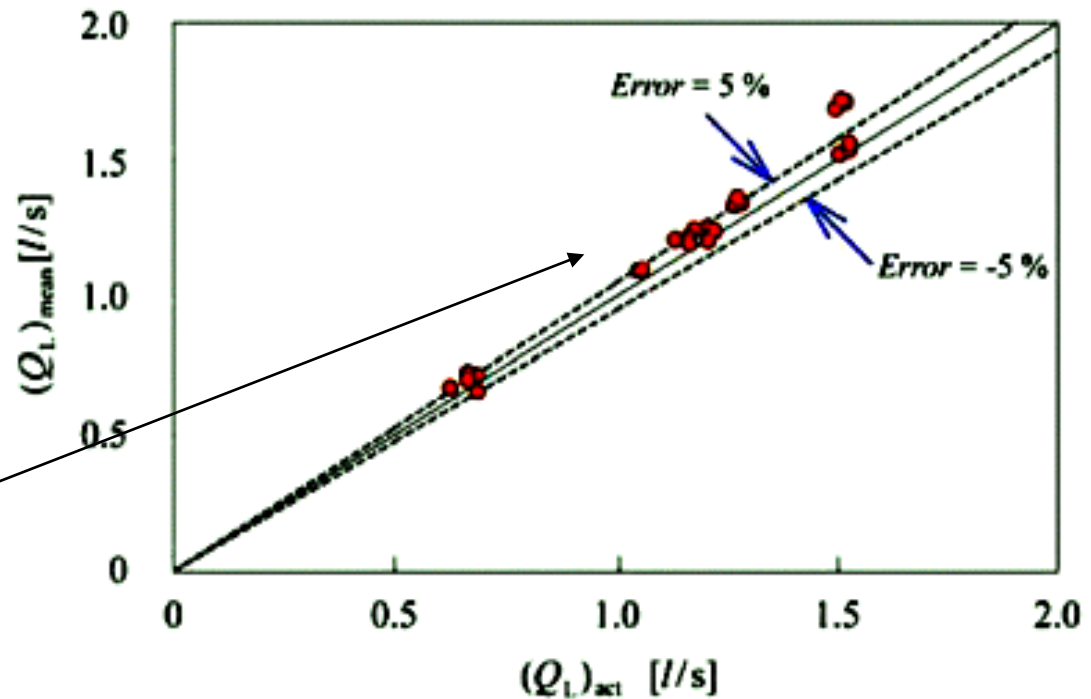
瞬時混相成分流量と時間平均流量



Q_{act}	Q_e	Q_v	ϵ_e	ϵ_v
1.9	1.91	1.84	0.5	-3.3
3.3	3.31	2.80	0.3	-17.9
5.1	5.04	5.12	-1.2	0.4
7.2	7.18	6.09	-0.3	-18.2

スラグ流の瞬時液相流量の波形

10秒間の平均流量計測結果の誤差範囲は5%



Gas flow metering

Relevance to velocity profile in a pipe

トレーサガスパルス注入による 天然ガスパイプラインの流量測定



Flow metering of natural gas pipeline by tracer gas pulse injection

村井 祐一

竹内 智朗



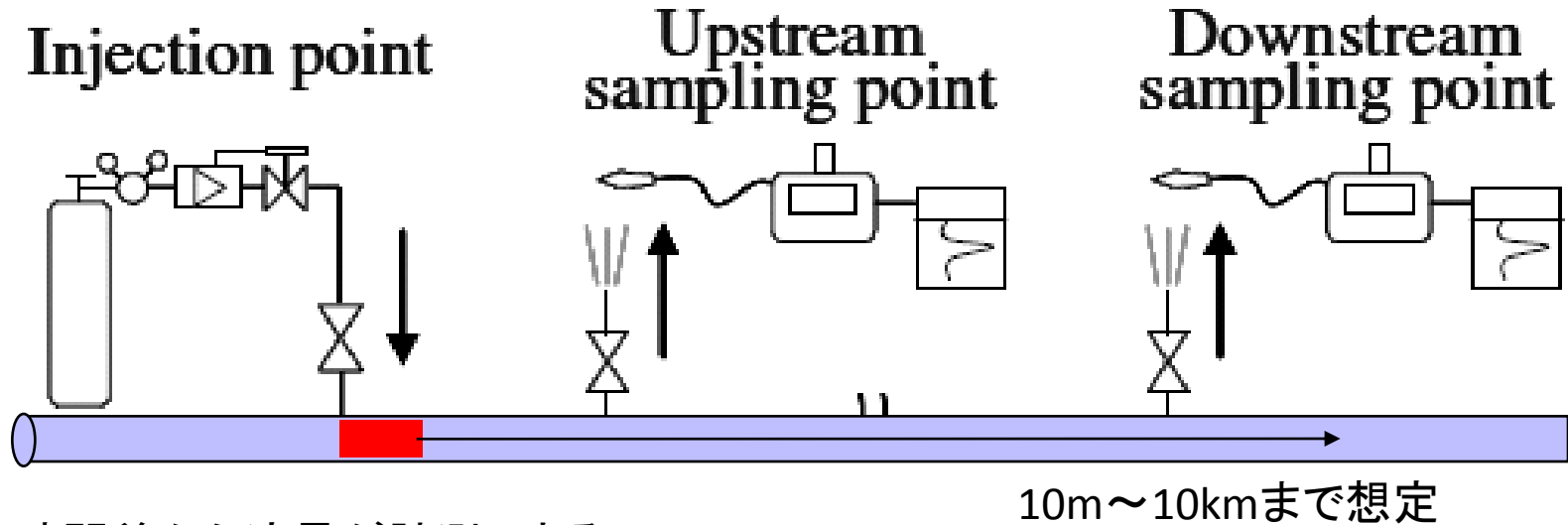
北海道大学
HOKKAIDO UNIVERSITY



注入点

検出点1

検出点2



時間差から流量が計測できる

10m~10kmまで想定

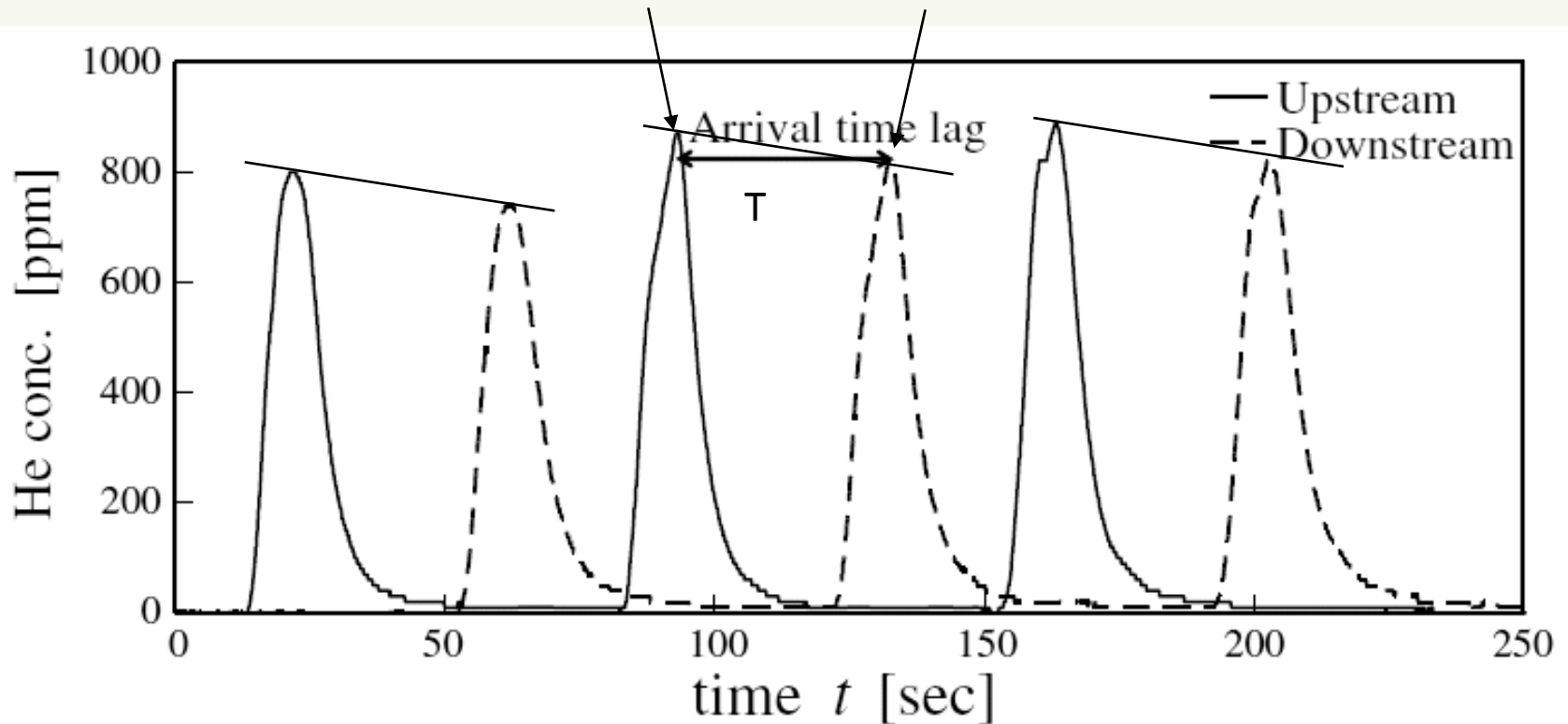
$$Q = \frac{1}{4}\pi \cdot D^2 \cdot \frac{L}{T} \rightarrow \frac{\Delta Q}{Q} = \sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + 4 \cdot \left(\frac{\Delta D}{D}\right)^2}$$

流量計測誤差は ΔT :パルスの通過時間差の計測誤差

実際のヘリウム濃度波形

D=80mm, W=6.0m/s, 注入点で1000ppm

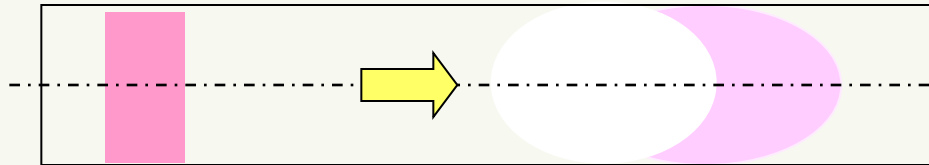
検出点1 検出点2



濃度上限: 1000ppm (燃焼影響), 濃度下限: 20 ppm (検出限界)

1次元的なパルスの移流を壊す管内の3次元流動

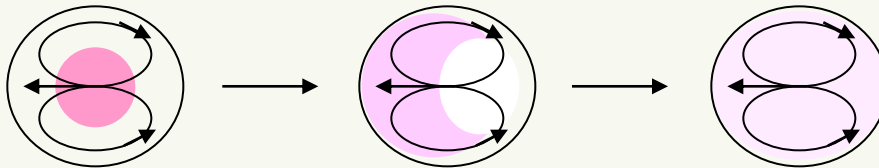
1. ストレート管における微量Heガスの乱流拡散



乱流拡散

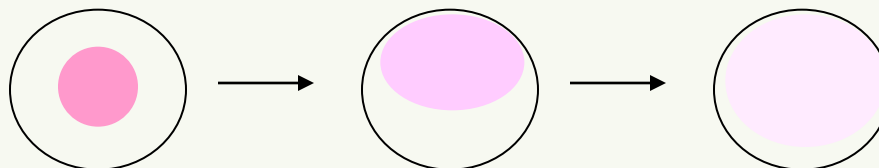
$l/d > 10000$

2. ベンド部におけるHeガスの偏在分布の影響



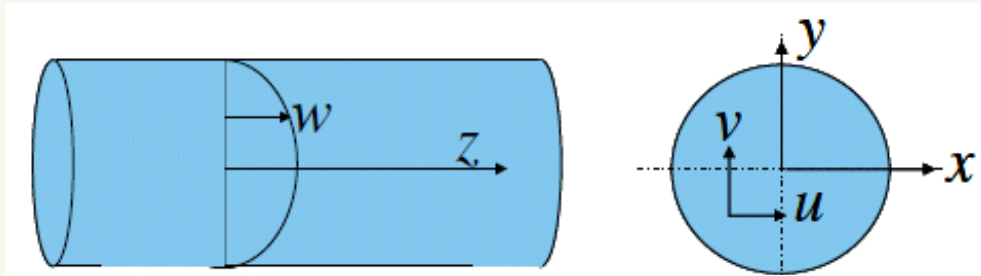
3次元混合

3. ストレート管におけるHeガスの浮力効果



密度差対流

パルスの乱流拡散の数値解析



$$\frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x} + v \frac{\partial \phi}{\partial y} + w \frac{\partial \phi}{\partial z} = \gamma \left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} \right);$$

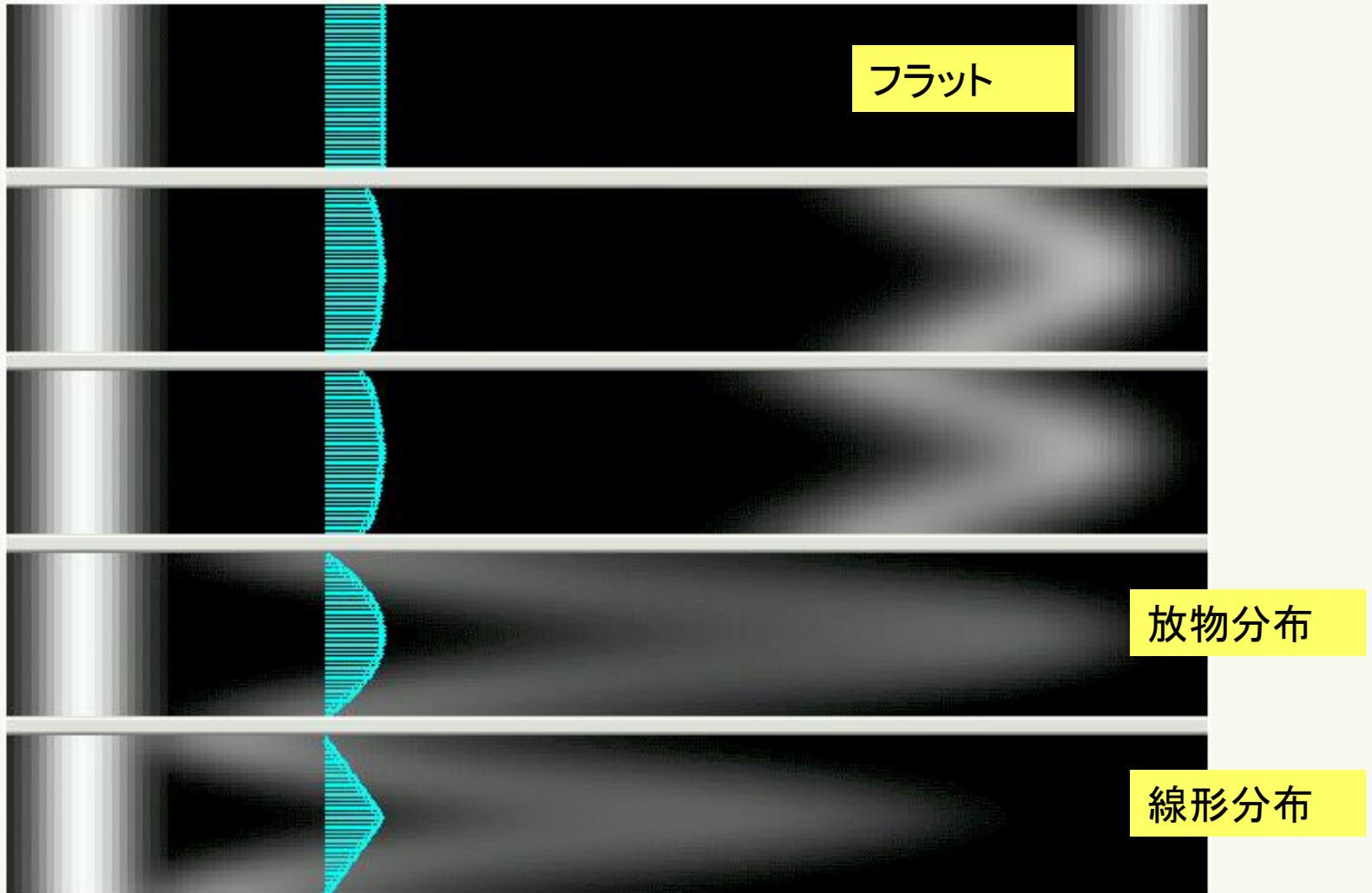
$$\phi = \phi(t, x, y, z). \quad (1)$$



1次元対流拡散方程式への換算

$$\frac{\partial \bar{\phi}}{\partial t} + W \frac{\partial \bar{\phi}}{\partial z} = D \frac{\partial^2 \bar{\phi}}{\partial z^2}; \quad \bar{\phi} = \bar{\phi}(t, z), \quad (2)$$

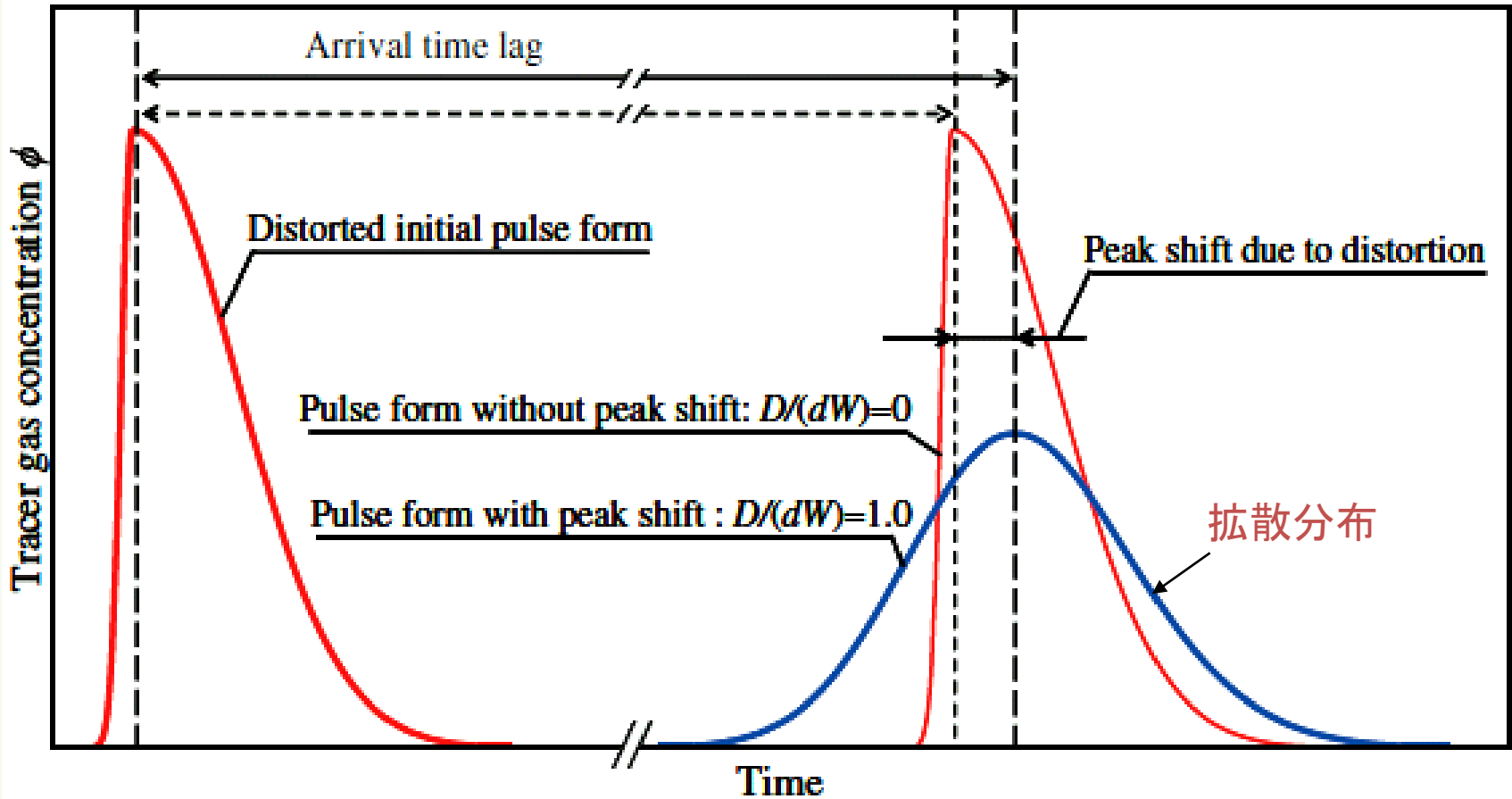
ガウス濃度分布の拡散過程



初期濃度

検出点1

検出点2



濃度上限: 1000ppm (燃烧影響)

濃度下限: 100 ppm (検出限界)

$D/(dW) = 1.0$ or 0 ,
 $T = 1000$ (s).

uGFlow

Ultrasonic Gas Flow meter

Flow rate (circular pipe)

$$Q = 2\pi \int_0^R v(r) r dr$$

→ **Measurement of velocity profile**

Flow rate (circular pipe)

$$Q = 2\pi \int_0^R v(r) r dr$$

→ Measurement of velocity profile

This is valid for gas too. → **uGFlow**

Measurement of velocity profile in a pipe

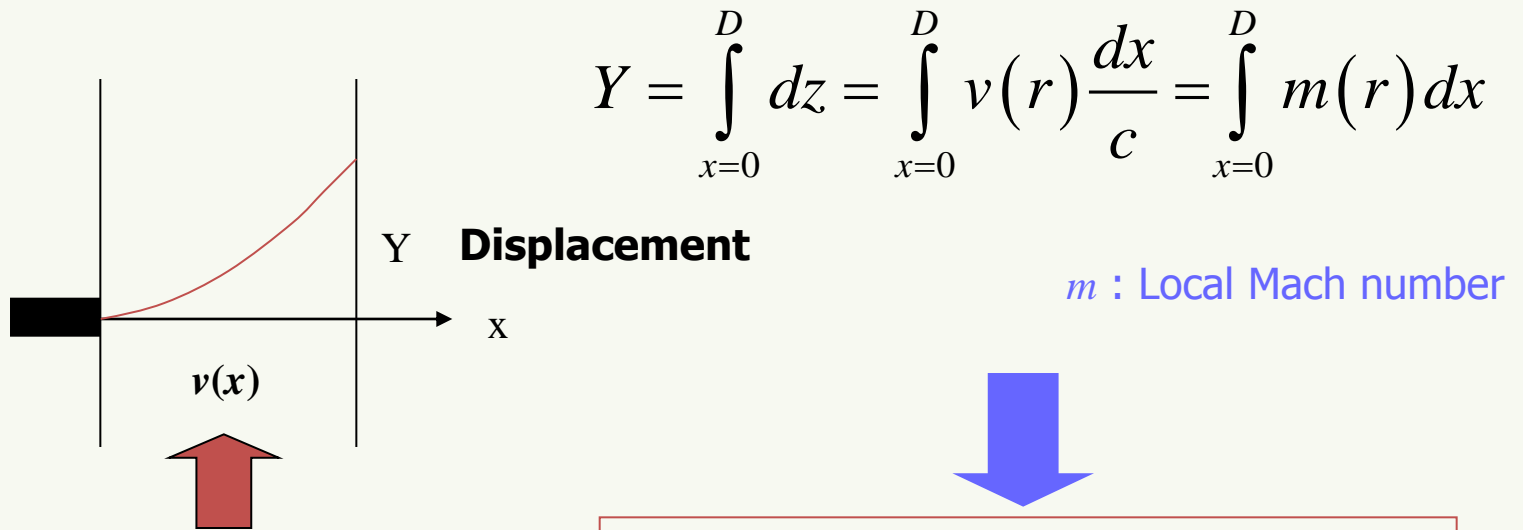
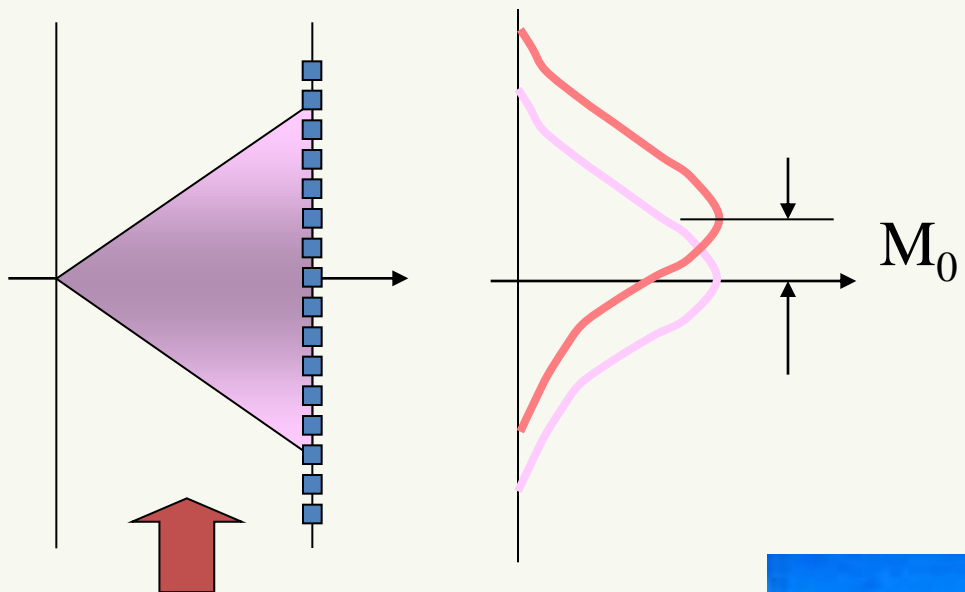


Fig. 2

Obtaining $m(r)$ is to perform a
Deconvolution of integral



Arrangement 1

Transducer array : $N \times M$

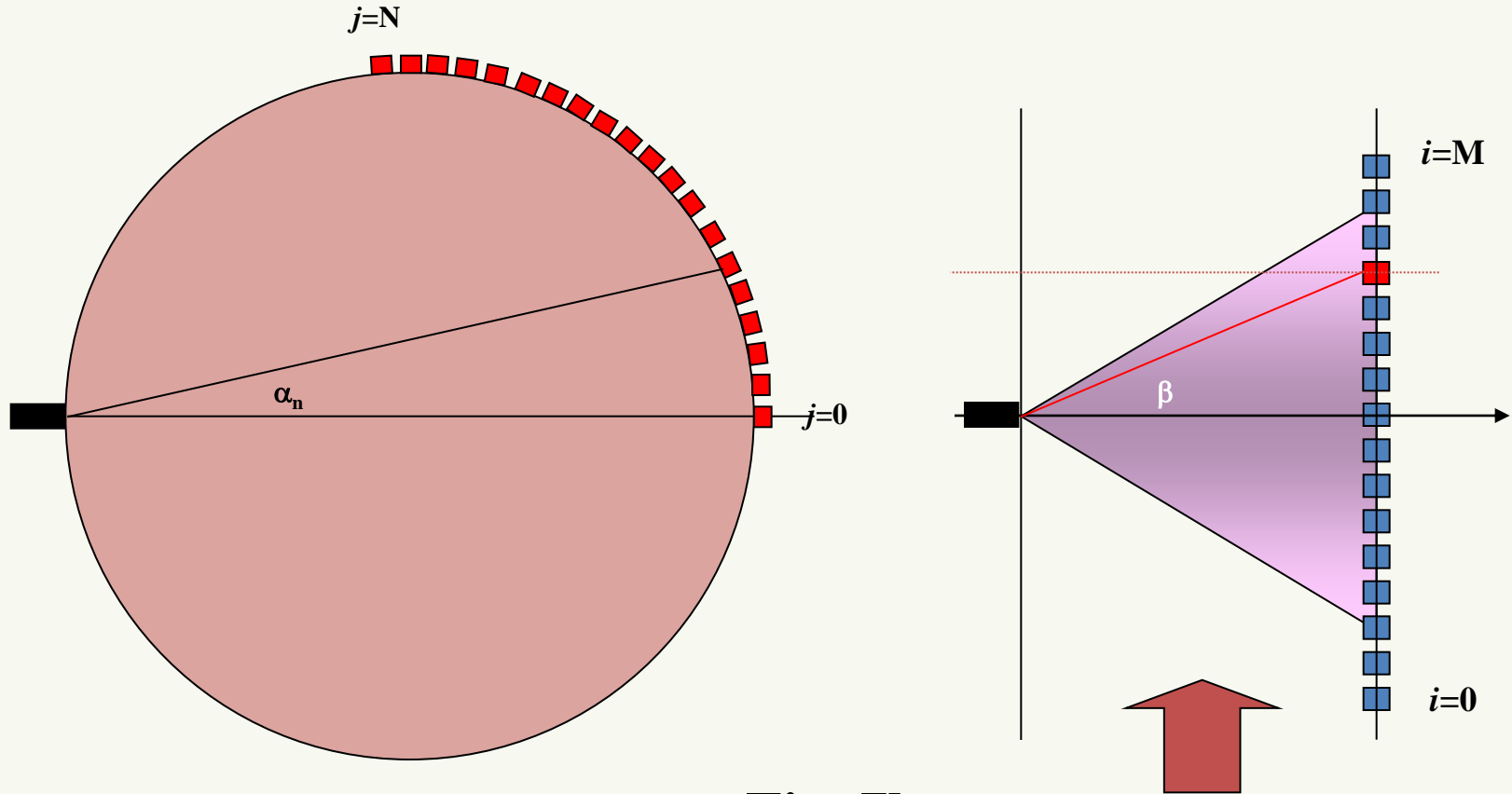
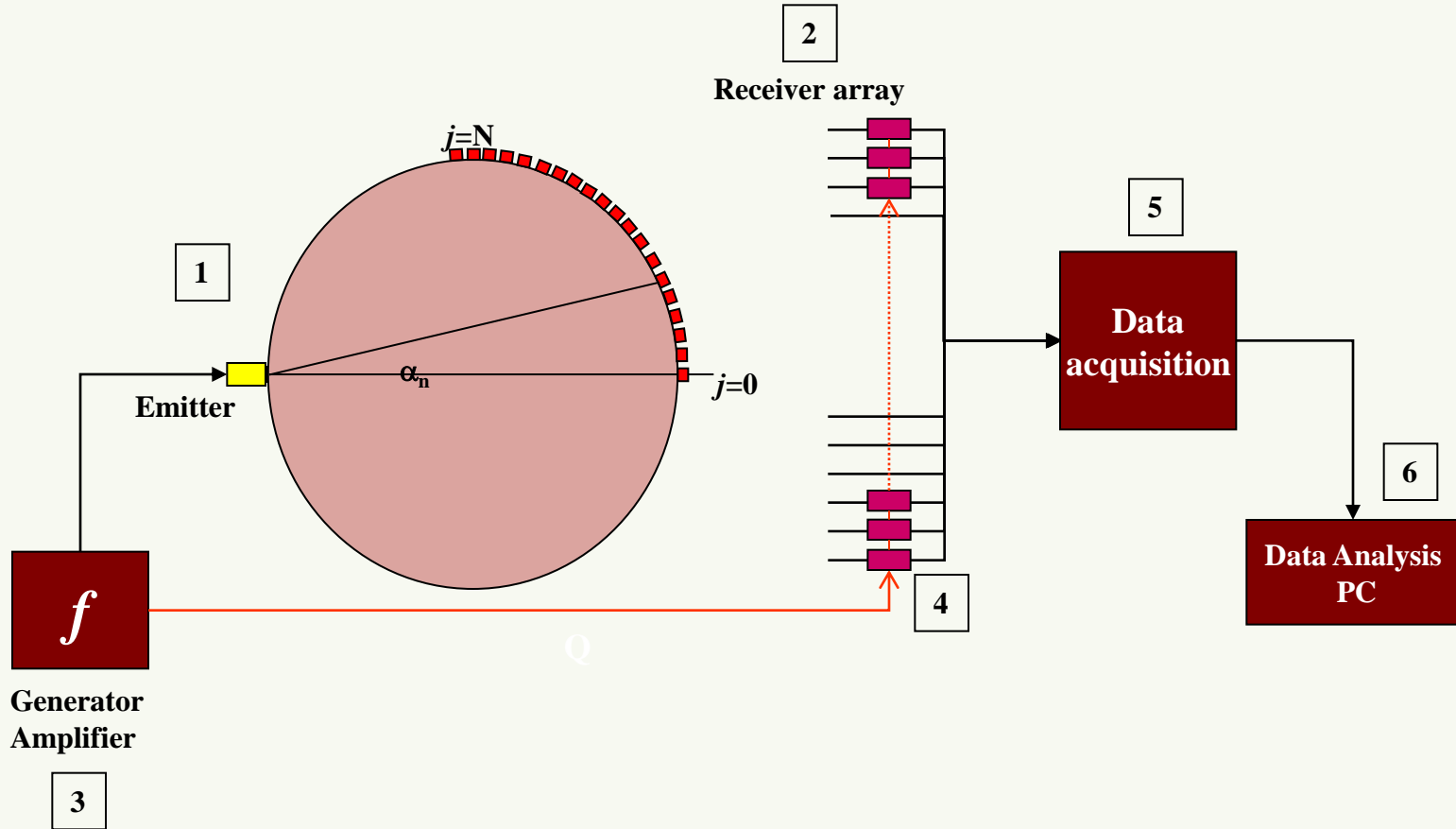


Fig. 7b

Construction-4
(Case 3)



Paradigm shift in flow metering

1. 流量計開発の歴史

流量計開発のルーツを探ると、計測技術、Vol.31、No.12「流量計測の歴史－1. 古代オリエント－」で述べたように数千年前にナイル河の流量を水位計（ニロメータ）で計測したことに始まるとされている。また流量計測の概念は、古代ローマでヘロン（ギリシア、前130～75）が流量は「流速×流路の断面積」であると提案し、ローマ水道の1日の送水量を99万 m^3 と計算したことに始まったとされている。しかし流速をどうやって計測したかは、筆者の調べた範囲では定かではない。

First principle

$$m = \rho \int \mathbf{v}(\mathbf{x}, t) \cdot d\mathbf{A}$$

$$\mathbf{v}(\mathbf{x}, t) : 3C3D$$

$$(V_x, V_y, V_z) \\ (x, y, z)$$

Flow meters developed

Ultrasonic method for Flow Measurement and **Flow metering**

Evolution of flow measurement technique has led to an acquisition of spatio-temporal information on flow field. : $V(r)$

Flow metering would naturally change the measurement principles from indirect to direct measurement of flow rate, as defined below

$$Q = 2\pi \int_0^R V(r) r dr$$

FlowBiz Research Inc. has been working to develop various types of flow meters as below, all based on the direct measurement.

single phase **Liquid**

uDFlow

With Tokyo Electric Power Co.

marketed



single phase **Gas**

uGFlow

patented

Gas & Liquid **multiphase**

uMFlow

With Hokkaido University

FIN