Dec. 2016, Tokyo

流速分布による流量計測 − A.Heronからの卒業

Paradigm shift in modern flow measurement and flow metering

Y.Takeda

Hokkaido University (ret)

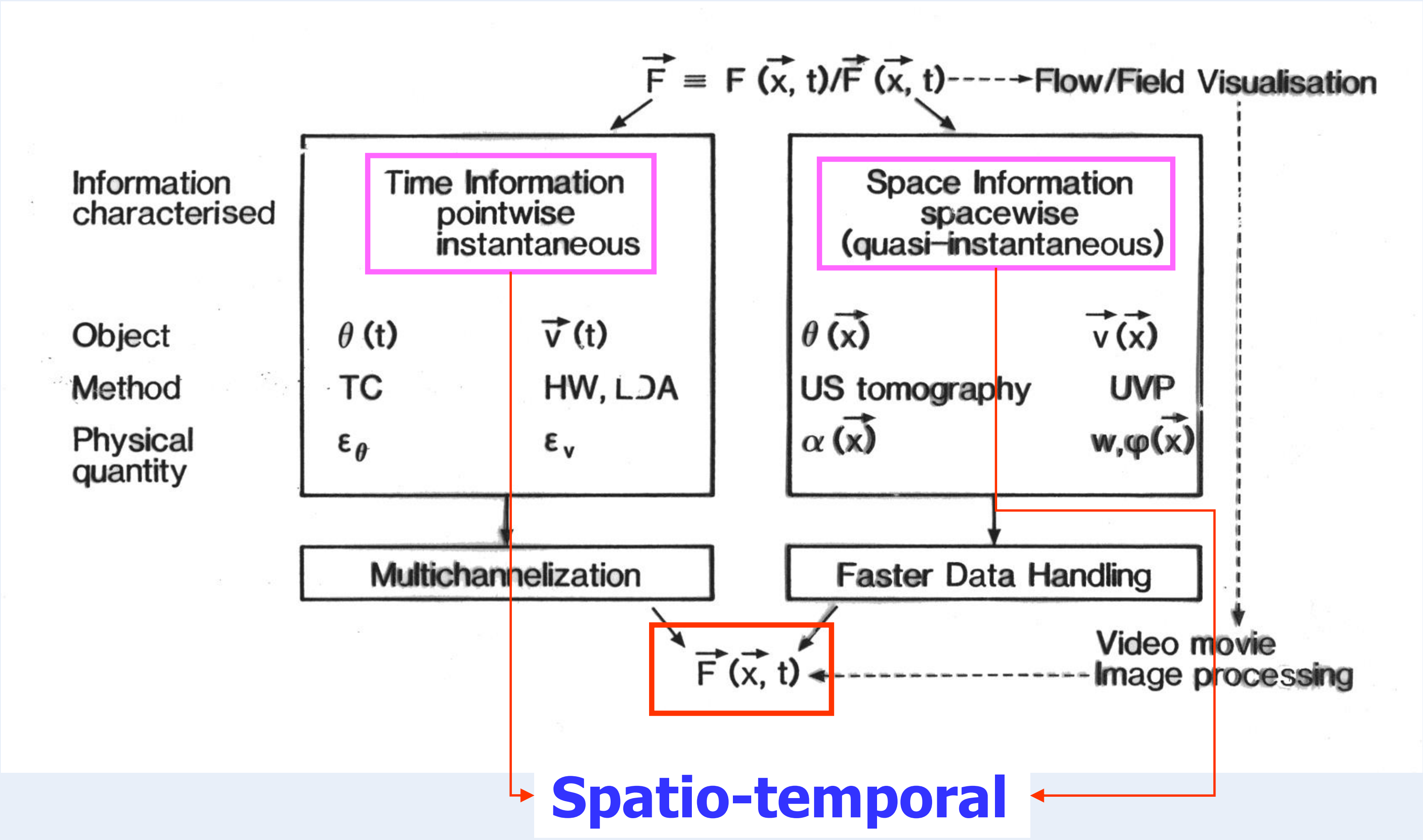
ETH Zurich

Paradigm shift in modern flow measurement and flow metering

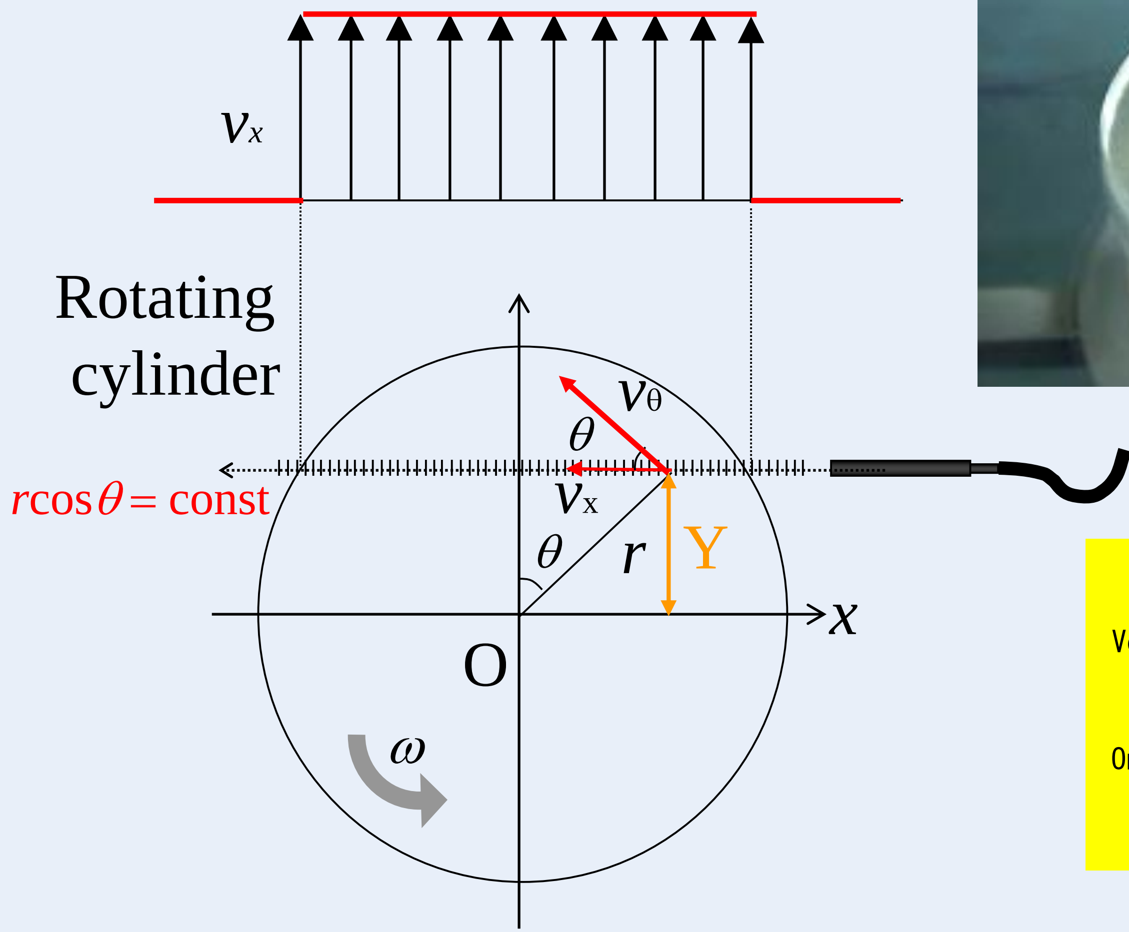
☆ Revolutionary change by
ultrasonic & laser applications

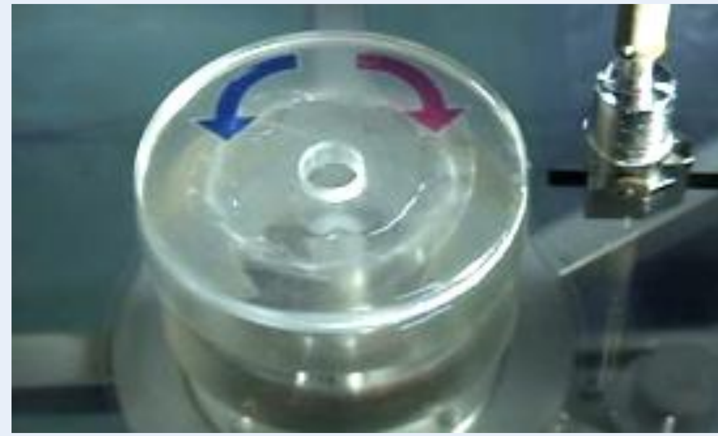
☆ **Back to the first principle**

Paradigm shift



Rotating Cylinder





$$v_\theta = r\omega$$

Velocity to be measured v_x

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

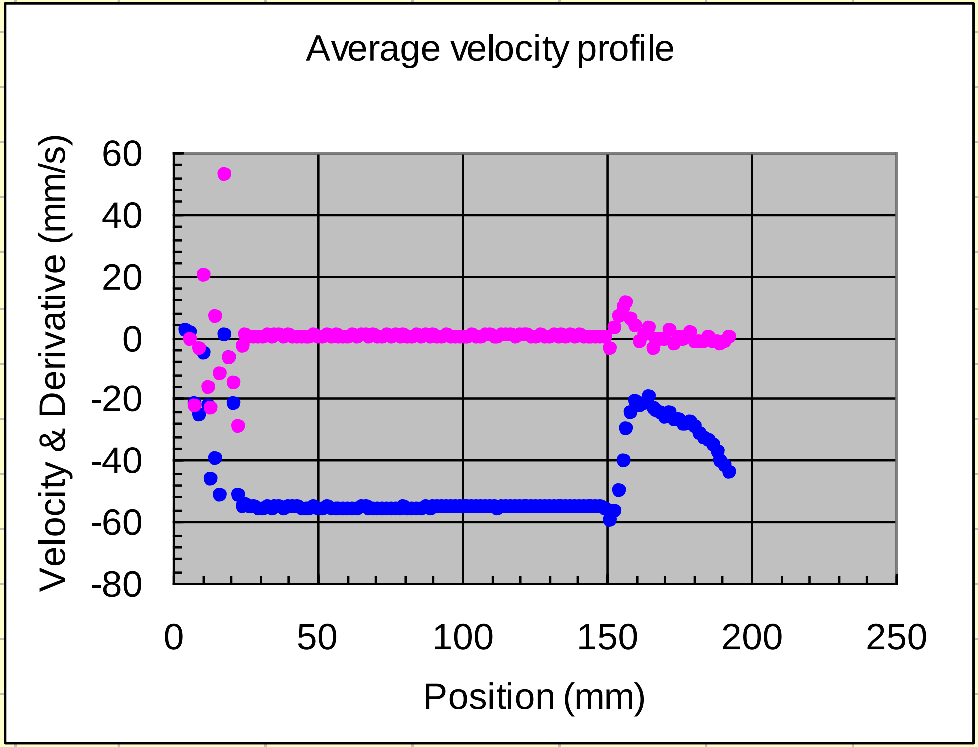
On the line where $r\cos\theta = \text{const}$

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

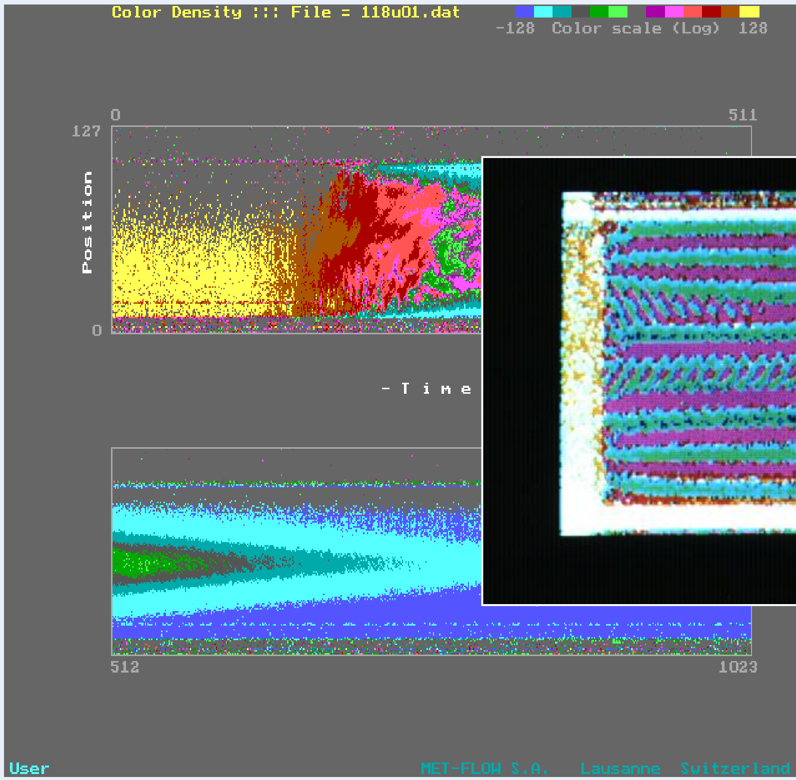
Rotating Cylinder

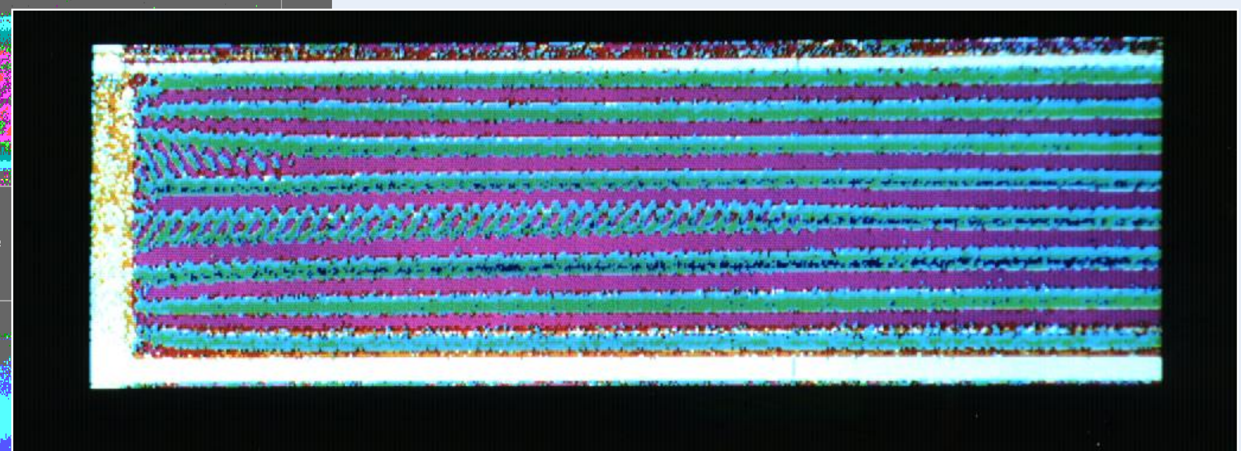
UVP : Accuracy - Velocity and Position
Velocity profile in a rotating cylinder

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%**	

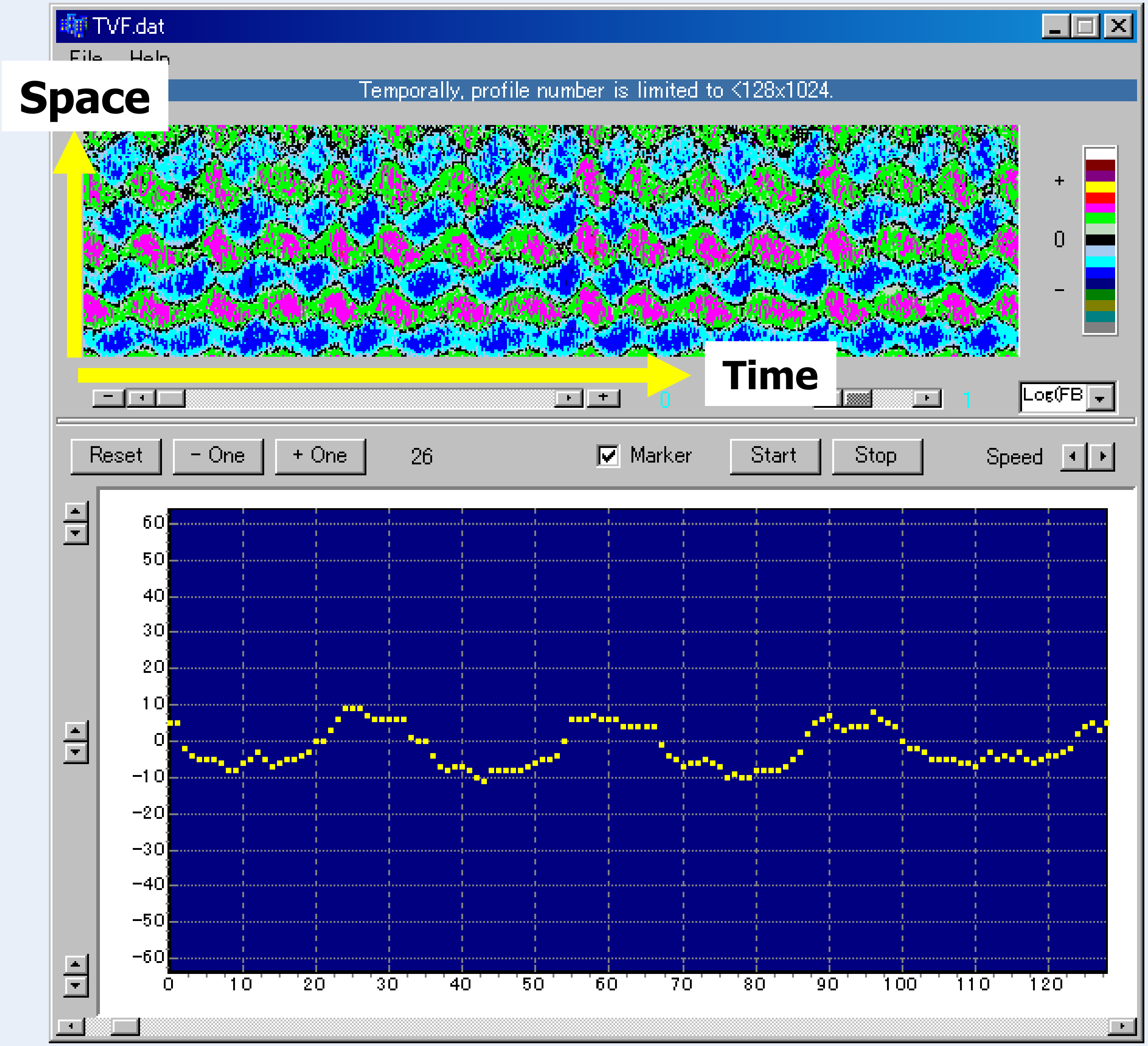


Spatio-temporal velocity field



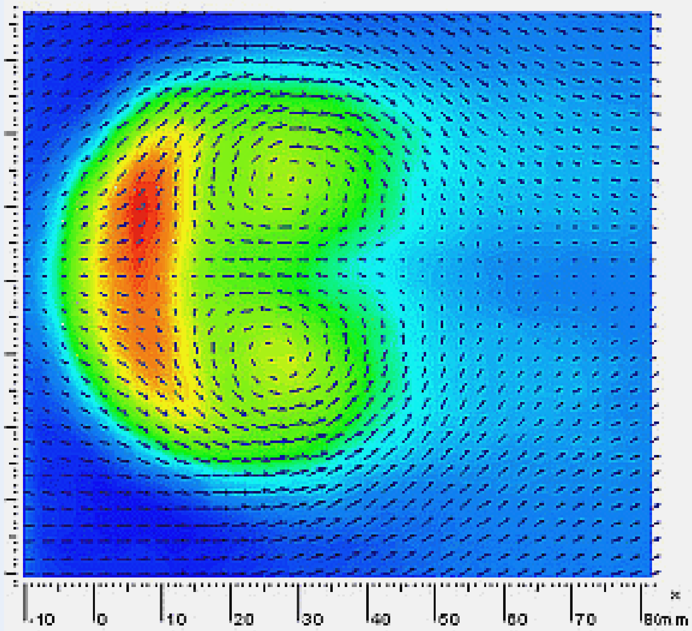


Spatio-temporal velocity field

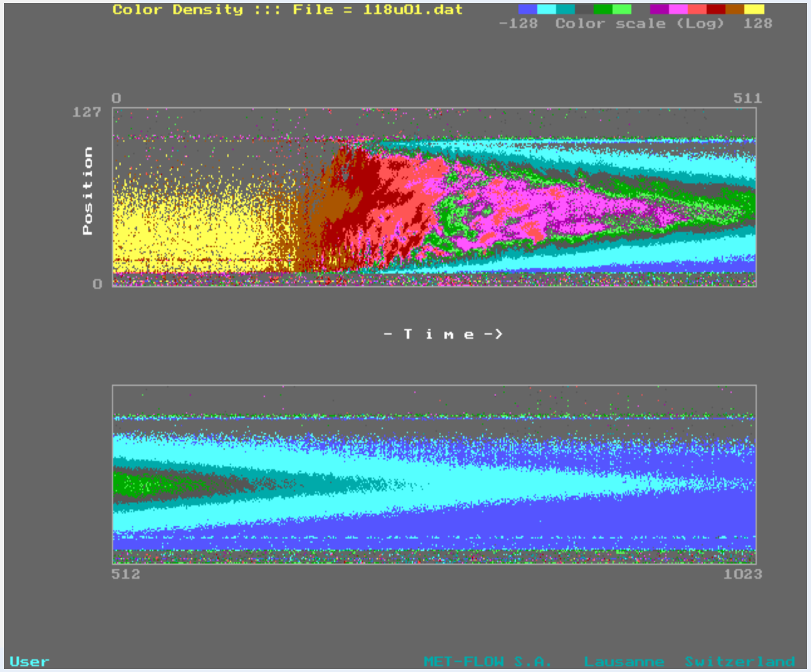


EFD → Measurement of flow field → $\boldsymbol{u}(\boldsymbol{x}, t)$

PIV(Laser)



UVP(ultrasound)



Fluid Dynamics

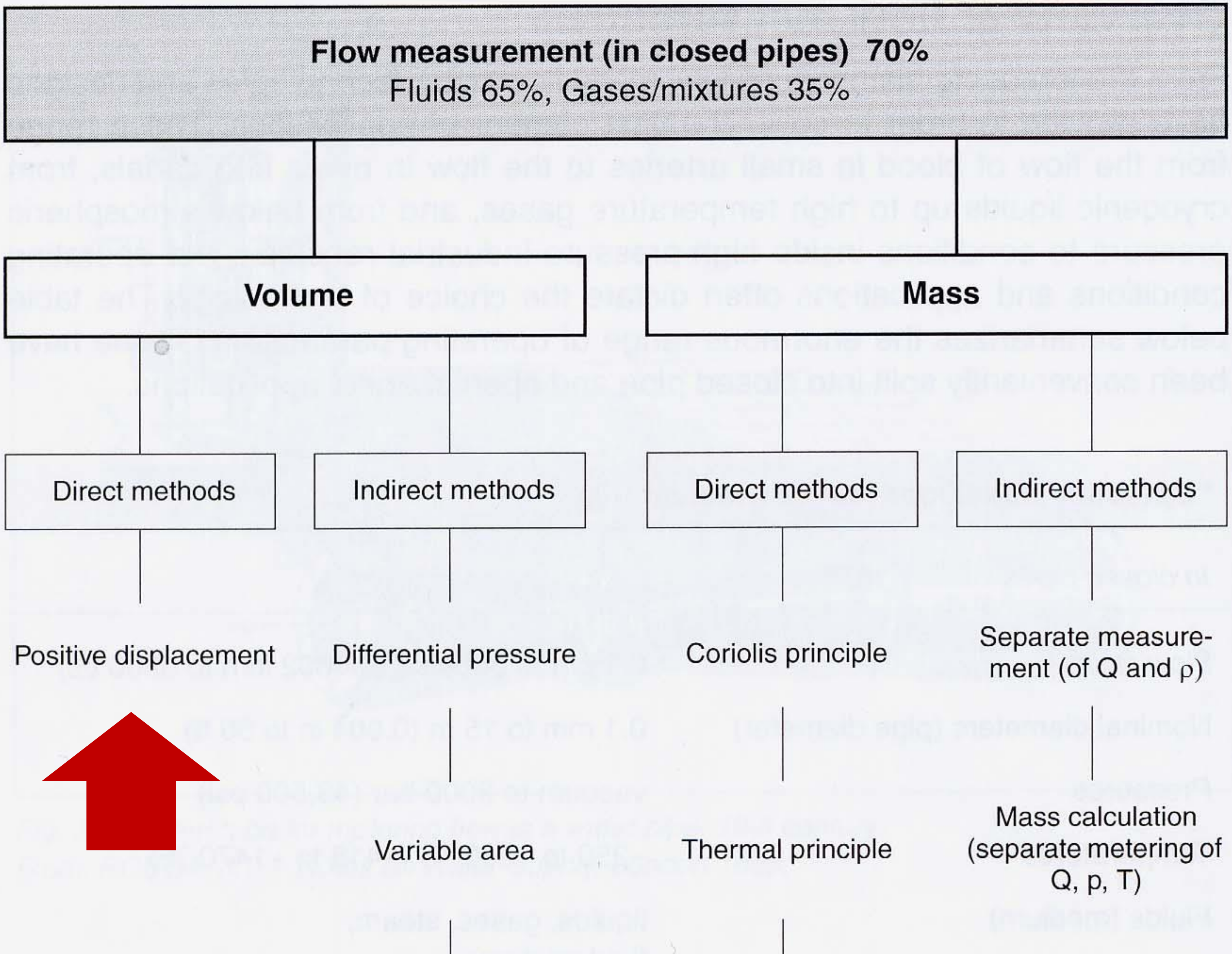
Methodology
Information flow in Fluid Mechanics

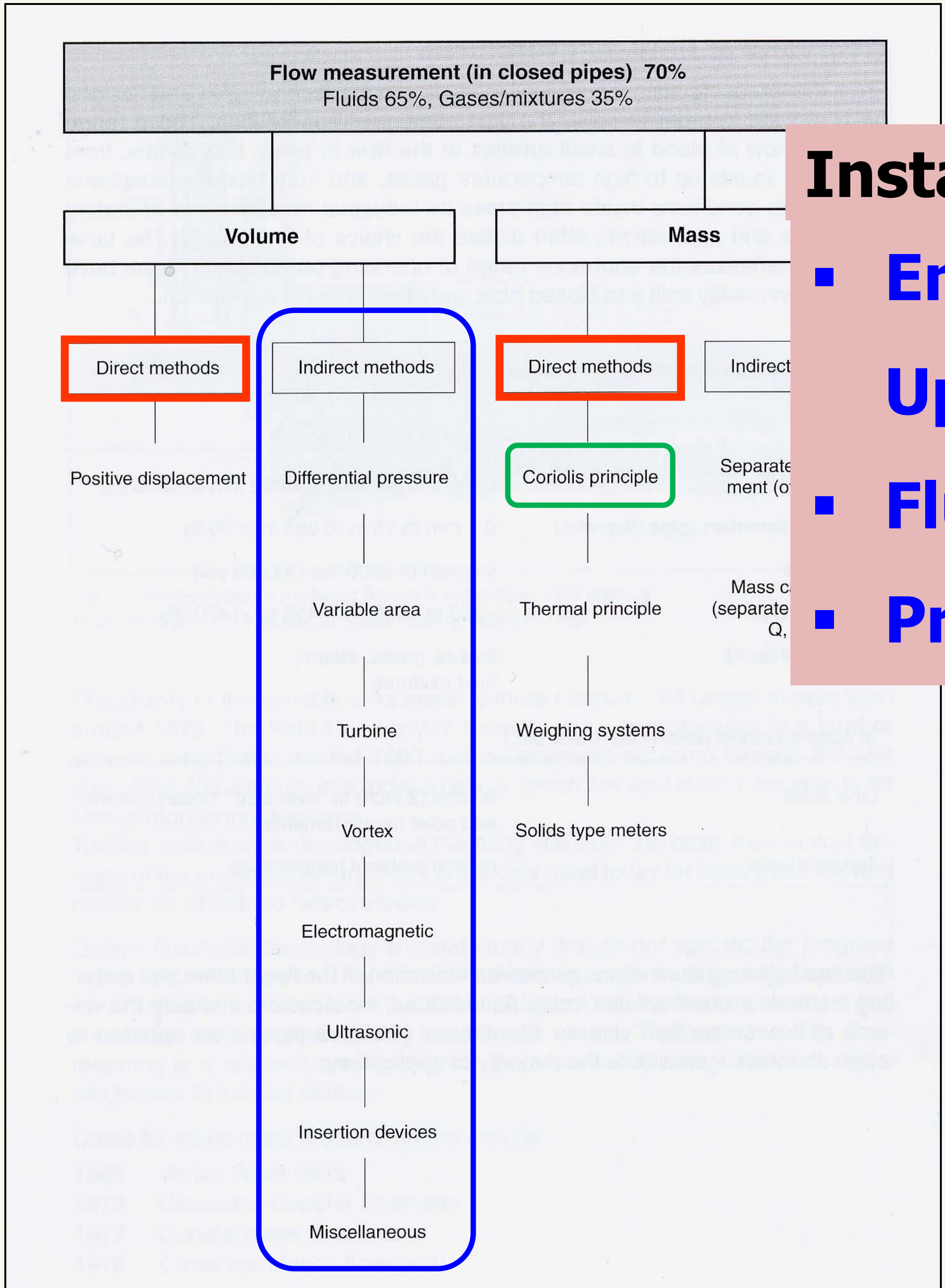
	Theoretical	Numerical	Experimental	
			Conventional	UVP/PIV
Image	⇑	⇑	●	⇑
Field	●	●	⇓	●
Physics	⇓	⇓	⇓	⇓

Flow metering

流量計測

UVP - udFlow

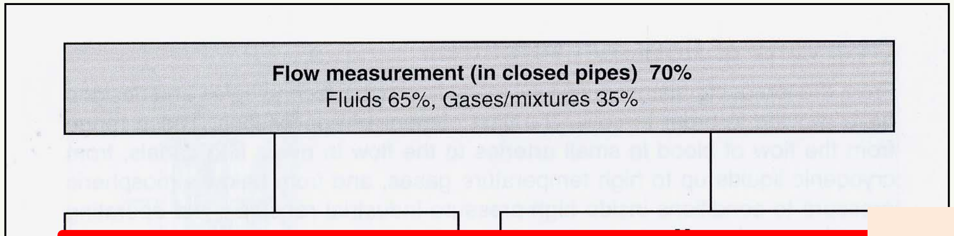

Flow measurement (in closed pipes) 70%
Fluids 65%, Gases/mixtures 35%
Volume
Mass
Direct methods
Indirect methods
Direct methods
Indirect methods
Positive displacement
Differential pressure
Coriolis principle
Separate measurement (of Q and ρ)
Variable area
Thermal principle
Mass calculation (separate metering of Q, p, T)



Installation condition

- **Entry length**

  Up/Downstream condition
- **Fluids – fully filling**
- **Precision/Accuracy**



PROCESS/FLOW NETWORK ABOUT US E-NEWS MAGAZINE SUPPLIERS RESOURCE EVENTS

Ultrasonic Flowmeter Piping Requirements

Ultrasonic flowmeters come in two basic types—Doppler and transit time. Doppler flo measure a frequency shift from beam reflections off bubbles or particles in a fluid. Tr time flowmeters measure the time difference between ultrasonic beams moving with against the flow. Clean fluid applications will generally rule out Doppler flowmeters. T time meters work well with clean and viscous liquids.

Flowmeters having multiple ultrasonic beams are less affected by flow profile disturb than single-beam meters. Excess solids or fluids with entrained gases may block the u pulses in transit-time meters. Raw wastewater applications, for example, usually have acoustic discontinuities for Doppler and are not clean enough for transit-time measur

Most recommendations call for fluid Reynolds numbers less than 4,000 (laminar flow) or above 10,000 (turbulent flow). Nonlinearities in the transition region between these two Reynolds numbers degrade meter accuracies.

Ultrasonic flowmeters are not applicable to slurries that are acoustically absorbent, such as lime or kaolin slurries. Highly absorbent solids attenuate the signal below usable strength.

The ultrasonic flowmeters should be installed upstream of flow obstacles, such as elbows, reducers, or valves. Ensure that the longest possible straight pipe is between the obstacle and the meter. The length of straight pipe can be reduced to five pipe diameters if an additional error of 1 percent maximum is acceptable.

Paying attention to these recommendations for flowmeter installations will help ensure successful applications with good accuracies.

This is the second article in a five-part series on the history and operation of flowmeter technology. Part III will appear in the June issue.

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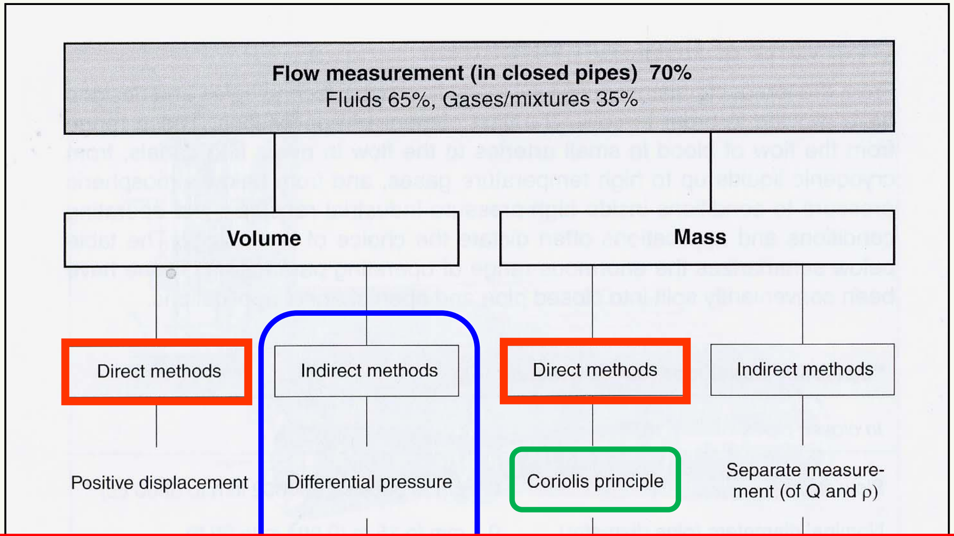
www.abb.com

Installation condition

- **Entry length**
  Up/Downstream condition
- **Fluids**
- **Precision/Accuracy**



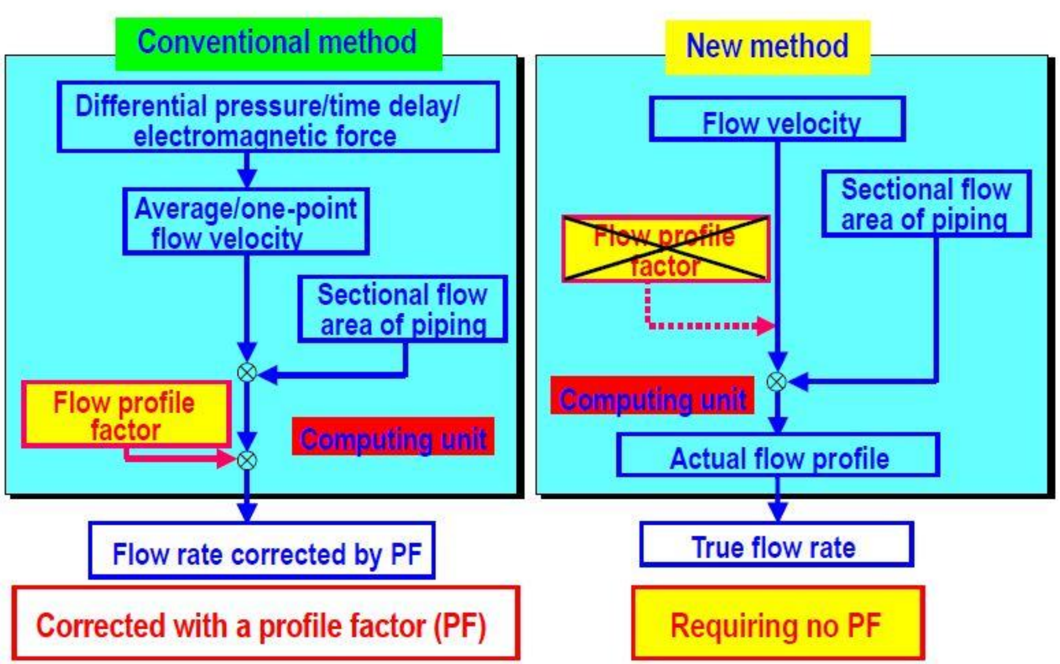


Figure 1 Conceptual comparison between conventional flowmeters and the flow-metering system by ultrasonic Pulse-Doppler profile-velocimetry.

Installation condition

- **Entry length**
  Upstream condition
- **Fluids**
- **Precision/Accuracy**

Profile Factor

ICONE14-89730

Factory Factor

ICONE14-89803

Paradigm in flow metering

By Heron of Alexandria
(Ἥρων ὁ Ἀλεξανδρεύς, 10-70 AD)

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
述べたように数千年前にナイル河の流量を水
ロメータ）で計測したことに始まるとされて
は、古代ローマでヘロン（ギリシ
が流量は「流速×流路の断面積」で
ーマ水道の1日の送水量を99万m^3
始まったとされている。しかし流速
したかは、筆者の調べた範囲では定

$Q = V \bullet A$
Flow amount = velocity x cross section

Paradigm shift in flow metering

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したかは、筆者の調べた範囲では定

Q = V • A

Flow amount = velocity x cross section

First principle

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

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

$(\boldsymbol{V_x}, \boldsymbol{V_y}, \boldsymbol{V_z})$
$(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$

Flow rate

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

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

$$(\boldsymbol{V_x}, \boldsymbol{V_y}, \boldsymbol{V_z})$$
$$(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$$

Flow rate measurement

Theoretical in conduit (pipe)

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

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

Measuring lines (i) are diameters at different angles.

Flow rate
(circular pipe)

Assuming Axisymmetry

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

$\rightarrow$ Measurement of velocity profile

Flow rate
(circular pipe)

Measurement of velocity profile promises

- ✓ High accuracy
- ✓ No entry length
- ✓ No calibration
- ✓ No site effect

Proceedings of ICONE 14
14^{th} International Conference on Nuclear Engineering
July 17-20, 2006, Miami, Florida USA

ICONE14-89682

ON THE ACCURACY EVALUATION OF ULTRASONIC DOPPLER FLOWMETER

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ABSTRACT

The accuracy evaluation of a pipe flowmeter using ultrasonic velocity profiler is investigated theoretically and experimentally. The error depends basically on the data points on discretized velocity profile, but it decreases rapidly with increasing the data points. It can be reduced, relative to the theoretical velocity profile, below 1% with about 100 data

swirling, well developed flow, perfect wall smoothness etc. and it is not the case for most of the plant conditions.

Conventional ultrasonic flowmeters adopt the principle of flight time of ultrasonic pulse to estimate a line average velocity of the flow, and the flow rate is estimated from it by multiplying the cross sectional area of the pipe [1]. Since it does not include any information about the velocity profile

Effect on Accuracy

The number of data points

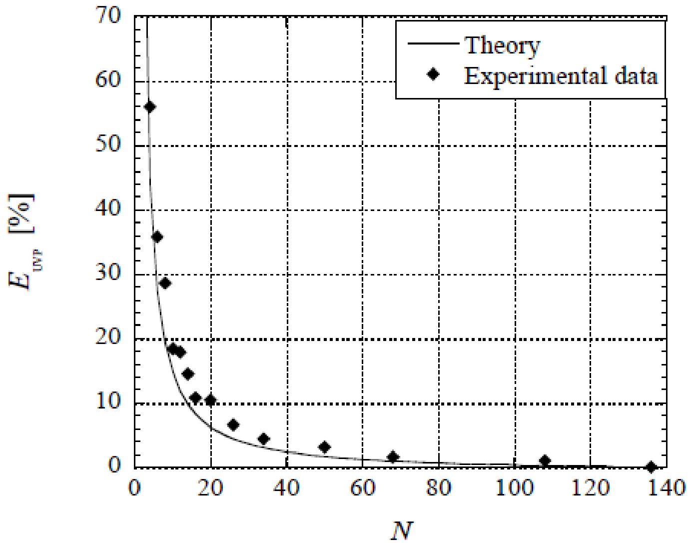

Fig. 2. Comparison between theoretical and experimental results on variation of error with respect to number of measuring points

The number of averaging time

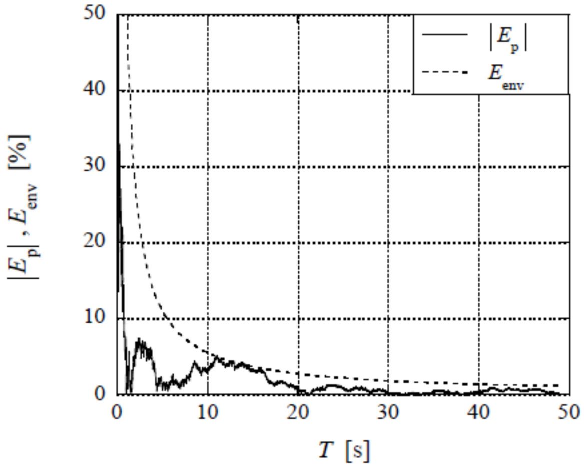

Fig. 10 Reduction of error with respect to measuring time T on simulation and experiment. Rotating frequency of pump rotor $f = 1.5$Hz

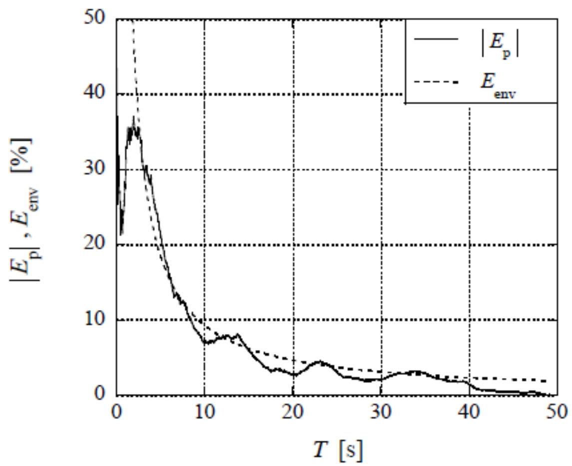

Fig.11 Reduction of error with respect to measuring time T on simulation and experiment; Rotating frequency of pump rotor $f = 3$Hz

Proceedings of ICONE 14
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ICONE14-89803

ON THE TRACEABILITY OF ACCURACY OF ULTRASONIC FLOWMETER

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ABSTRACT

Time-of-flight ultrasonic flowmeters have been widely used these days in industry. It is however in suspicion if its high accuracy is tracable to the national standard. It was made clear why traceability cannot be guaranteed from a fluid mechanical point of view. The main reason is a difference of flow configuration between the flow standard and the measurement position *on-site*. The concept of 'Facility Factor' is introduced and it is concluded that the 'Profile Factor' is not sufficient for correcting the meter reading. It is discussed that measurement of velocity profile *on-site* is essentially required.

INTRODUCTION

Ultrasonic flowmeter has been established and accepted by industry. Its usage is growing and diversified in recent years.

suppose, then, this expression of Eq.(1) is too crude to obtain the flow rate with high precision.

The PF is usually calibrated using the standard facility [2] or other facility where the flow rate and its uncertainty are tracable to the national standard [3]. The instrument providers claim that PF can be calibrated as less than 0.5% of accuracy by a careful preparation of calibration procedure and the post-processing of the results and that it is tracable to the national standard. It is known, however, that the PF is dependent on the Reynolds number of the flow [4], which reflects the fact that the PF sensitively depends on the velocity profile in a pipe.

Since the standard facility has a limited range of Reynolds number to be used for such a calibration, and normally the upper limit to be attained is lower than the actual Reynolds number to be measured, an extrapolation procedure has to be

A flow rate derived by the instruments is represented as

‘Facility factor’ must be introduced.

propagation speed of the ultrasonic pulse and expressed using an operator as

$$Q_{MUT} = F\left[V_M\left(r,t\right)\right]. \qquad (5)$$

V_M is a velocity distribution at the measurement points of the facility and a function of radial position and time. Here is assumed an axial symmetry. Since the instrument does not regard the velocity profile, P is introduced and called a ‘profile factor’ (equivalent to K of Eq.(1)). P is treated as a function of Reynolds number $P(Re)$ and obtained experimentally using a calibration facility as

$$P \equiv \frac{Q_A}{Q^A_{MUT}}. \qquad (6)$$

A suffix A means the value at the calibration facility so that Q_A is treated as the true value.

Q_{MUT} here is represented using an operator as

$$Q^A_{MUT} \equiv F\left[V_A\right] \qquad (7)$$

for the velocity profile at the calibration facility.

In the similar manner, a measured flow rate *on-site* is given as

$$Q^S_{Read} = P \bullet Q^S_{MUT} \qquad (8)$$

This is expressed using Eq.(6) as

$$Q^S_{Read} = P \bullet Q^S_{MUT}$$

$$= \frac{Q_A}{Q^A_{MUT}} Q^S_{MUT} \qquad (10)$$

$$= Q_A \frac{F\left[V_S\right]}{F\left[V_A\right]}$$

This does not reproduce the true value!

This is due to a fact that the velocity profile is not identical to that *on-site*. Namely, it reflects the fact that V_A is different from V_S.

$$Q^S_{Read} = \frac{F\left[V_A\right]}{F\left[V_A\right]} \frac{Q_A}{Q^A_T} Q^S_{MUT}. \qquad (12)$$

FACILITY FACTOR

As defined in Eq.(10), the **facility factor** is for correcting a difference of flow configuration, namely velocity profile, pipe geometry, surface roughness etc. between the calibration facility and the measurement position *on-site*;

$$R \equiv R\left(\mathrm{Re}, Geometry, temporal\ fluctuation, etc.\right).$$

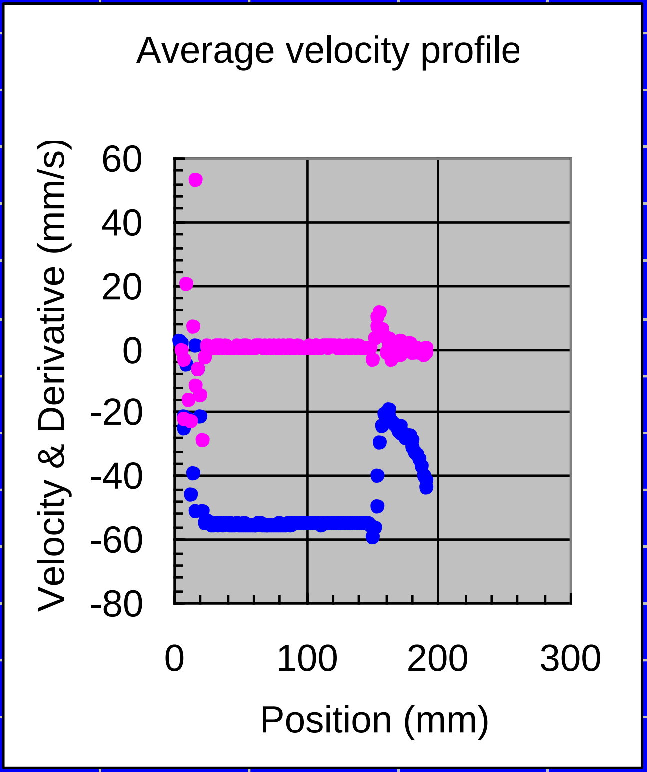
Among them, geometry difference is twofold; one is a deviation of true cylinder for both locations, which can be readily measured and generally negligible. Especially for the spool type instrument, this effect is eliminated by calibrating the instrument including the pipe to be used. The other is a configuration of upstream piping. This might be more influential and less definable. For the case where very high precision is required, this problem is recognized and carefully calibrated. Bends and elbows at the upstream cause a diversion of velocity profile from axisymmetric distribution, often referred as swirling effect, which is substantially the main reason for the error of flow rate measurement. The influence of such a swirling effect by upstream configuration has been extensively investigated by flow standard institutes [5] as well as instrument providers [6]. It seems, however, difficult to generalize the problem and there appears no clue to the solution.

The swirling effect seems not to be clearly recognized that there are two factors of swirling; a flow vector becomes three-dimensional, namely it is a breaking of an assumption of one-dimensional flow and 3-components vector has to be treated; $\boldsymbol{v} = \left(v_r, v_\theta . v_z\right)$. Another is that the flow distribution becomes non-axisymmetric. Namely a velocity profile is not a single variable function but (at least) a two-variable function as (r, θ). The former might be relaxed by using flow straightener and sufficiently long entry length upstream the measurement position except for the turbulent fluctuation. The influence of the latter seems to have been traditionally trusted to be less

Principles

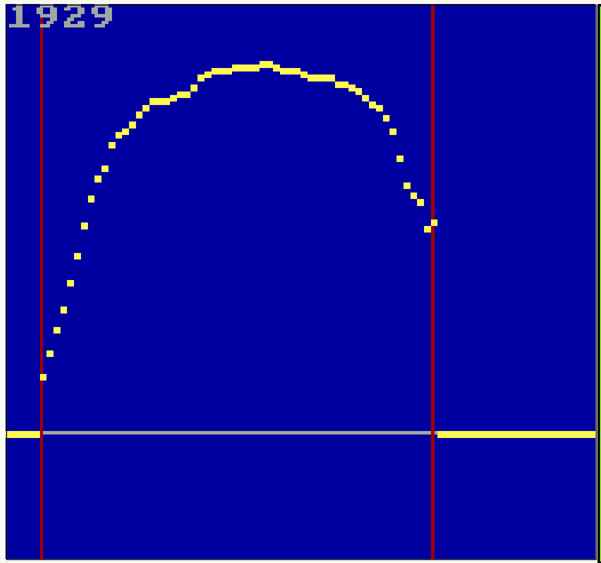
- Ultrasonic
- UVP
- udFlow

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%**	



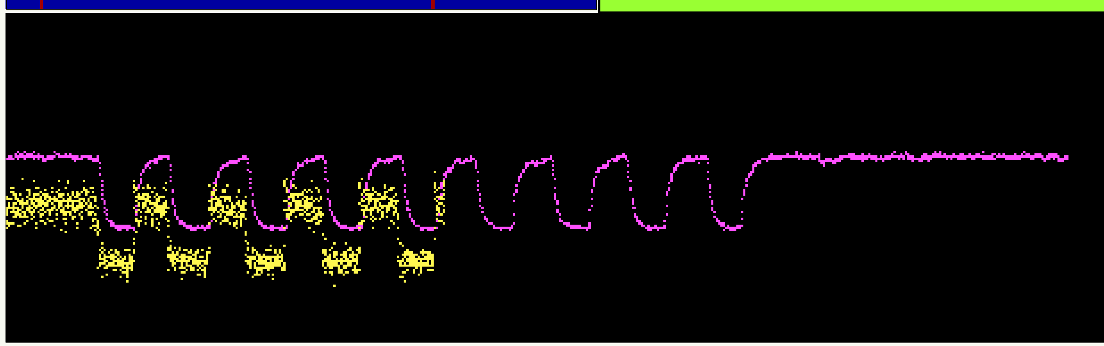
Small pipe

Profile and flow rate



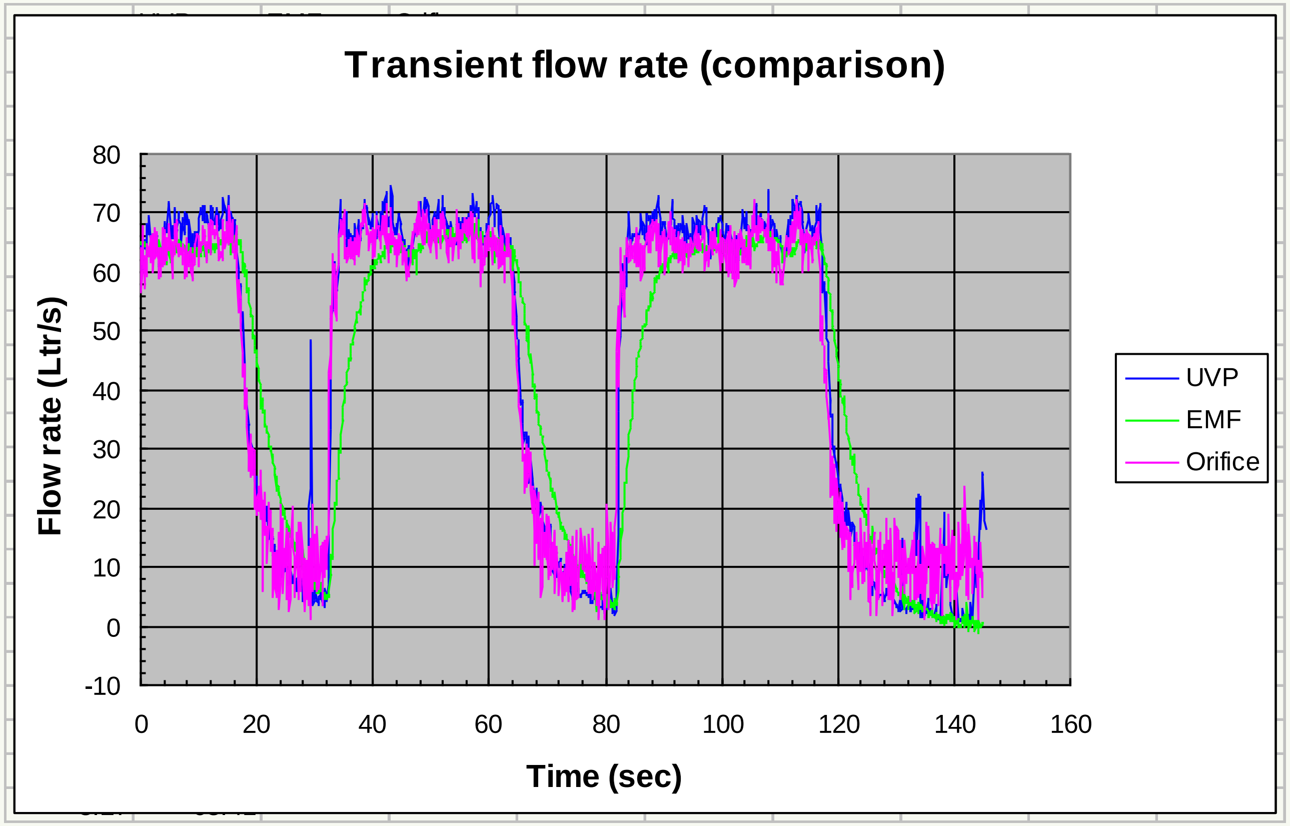
File : tp3004.dat
: 3328(Profs)
Angle : 15.0 (deg)
cor. : 3.864
FS Q : 2.0 (Ltr/s)
Time : 300 (sec)
Wall : 5
to : 62

Q= 0.94 Ltr/s at 115.74

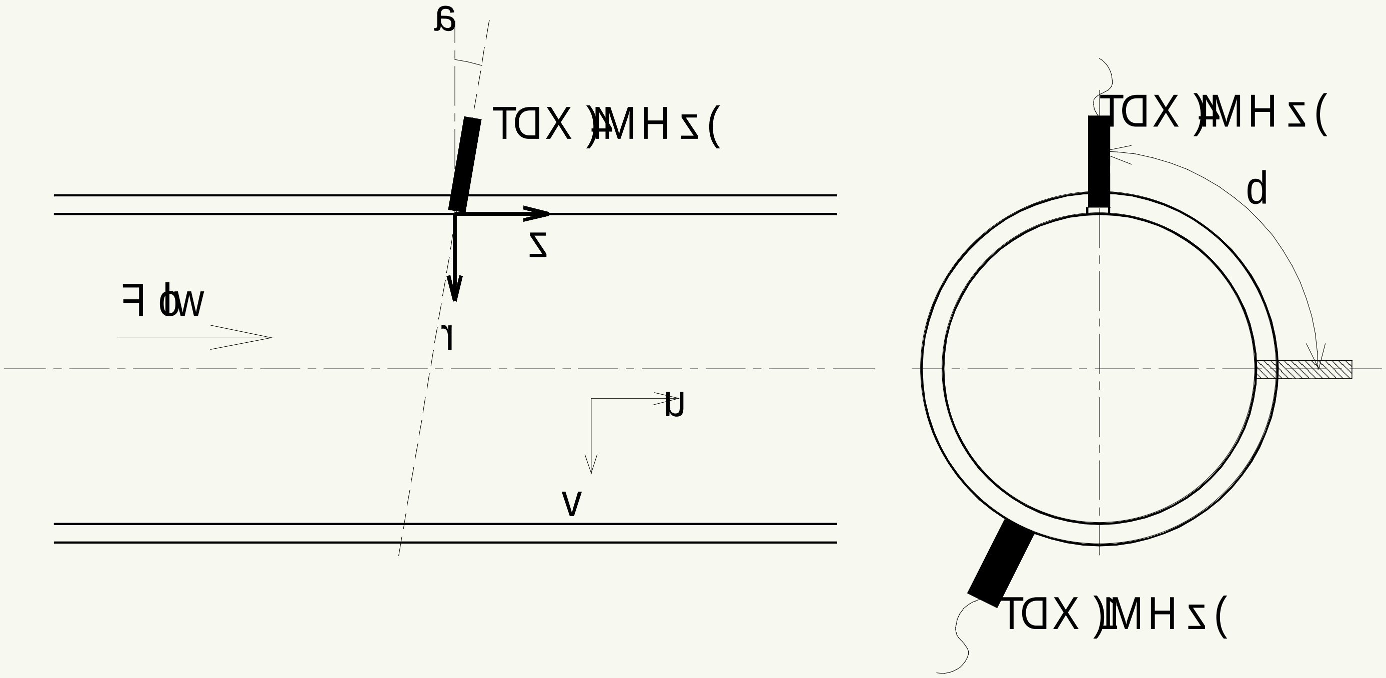


Flow rate measurement using UVP

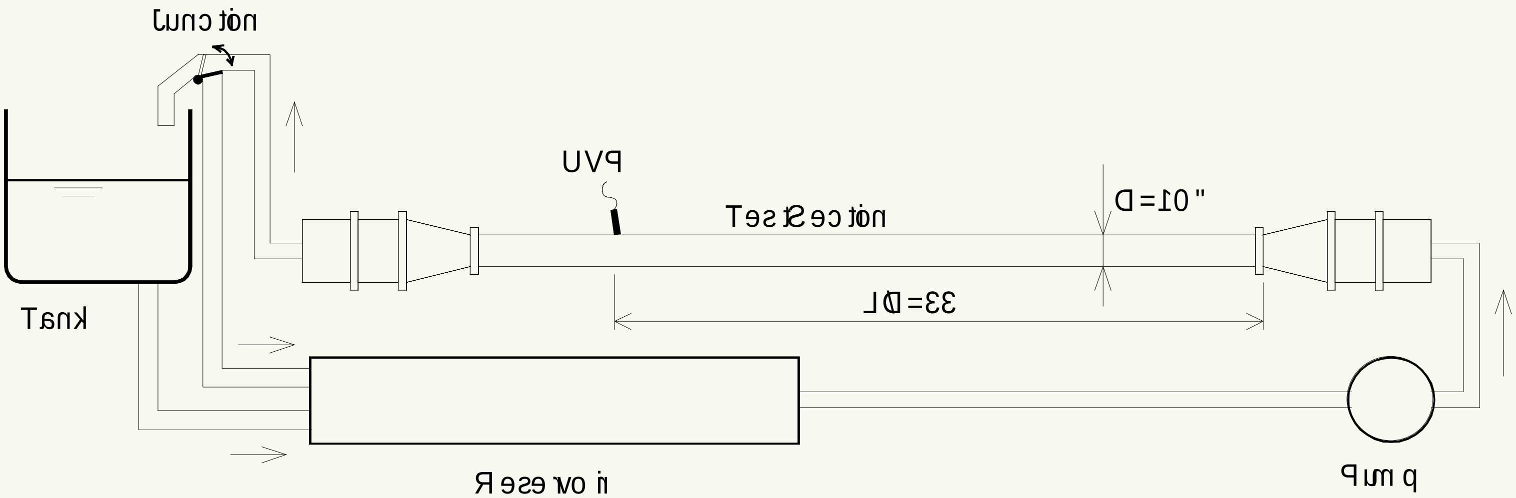
500A SUS pipe



@NIST

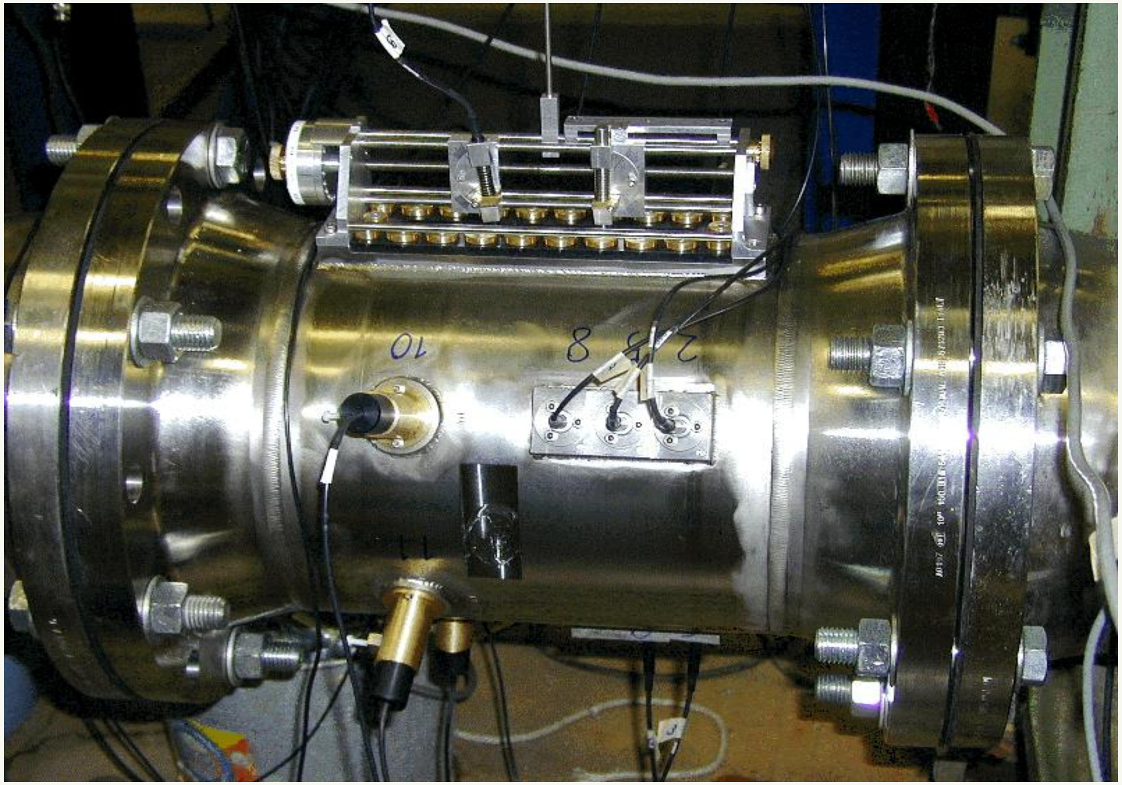


Test section detail and coordinate system

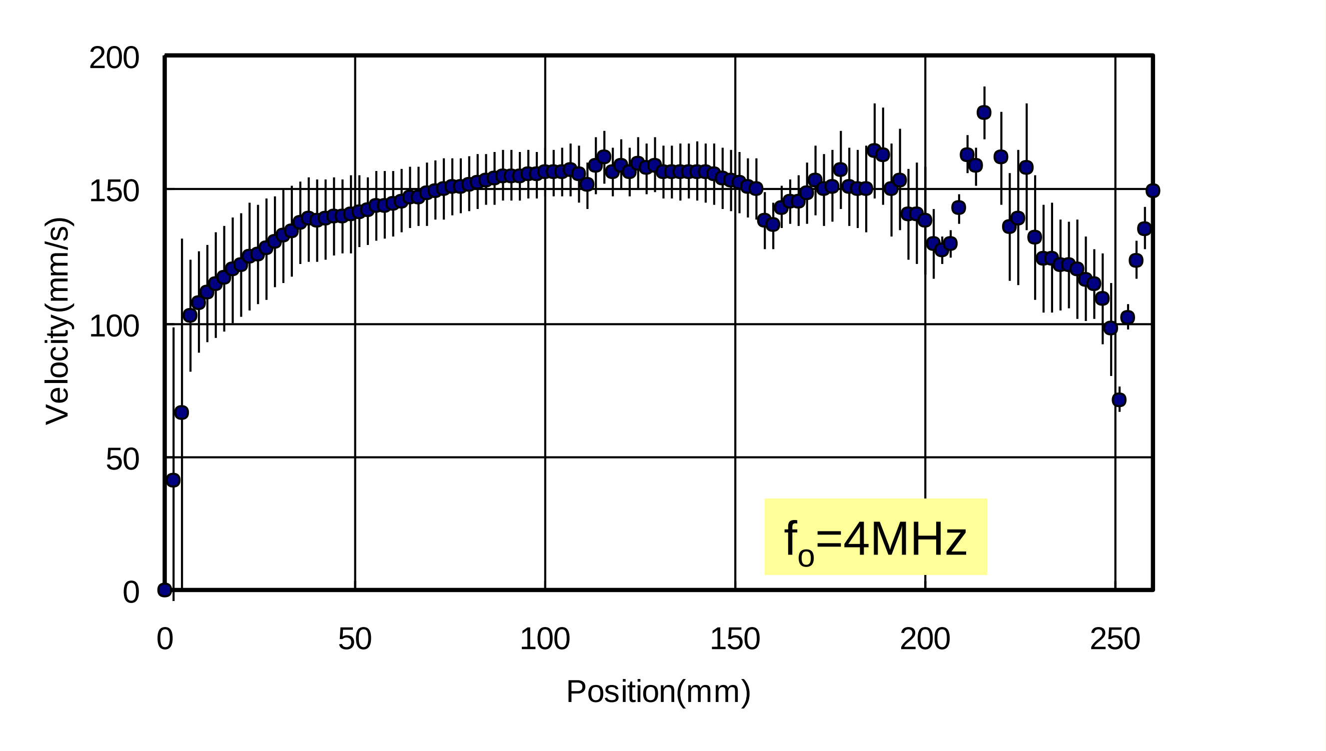


Schematic of the experimental apparatus

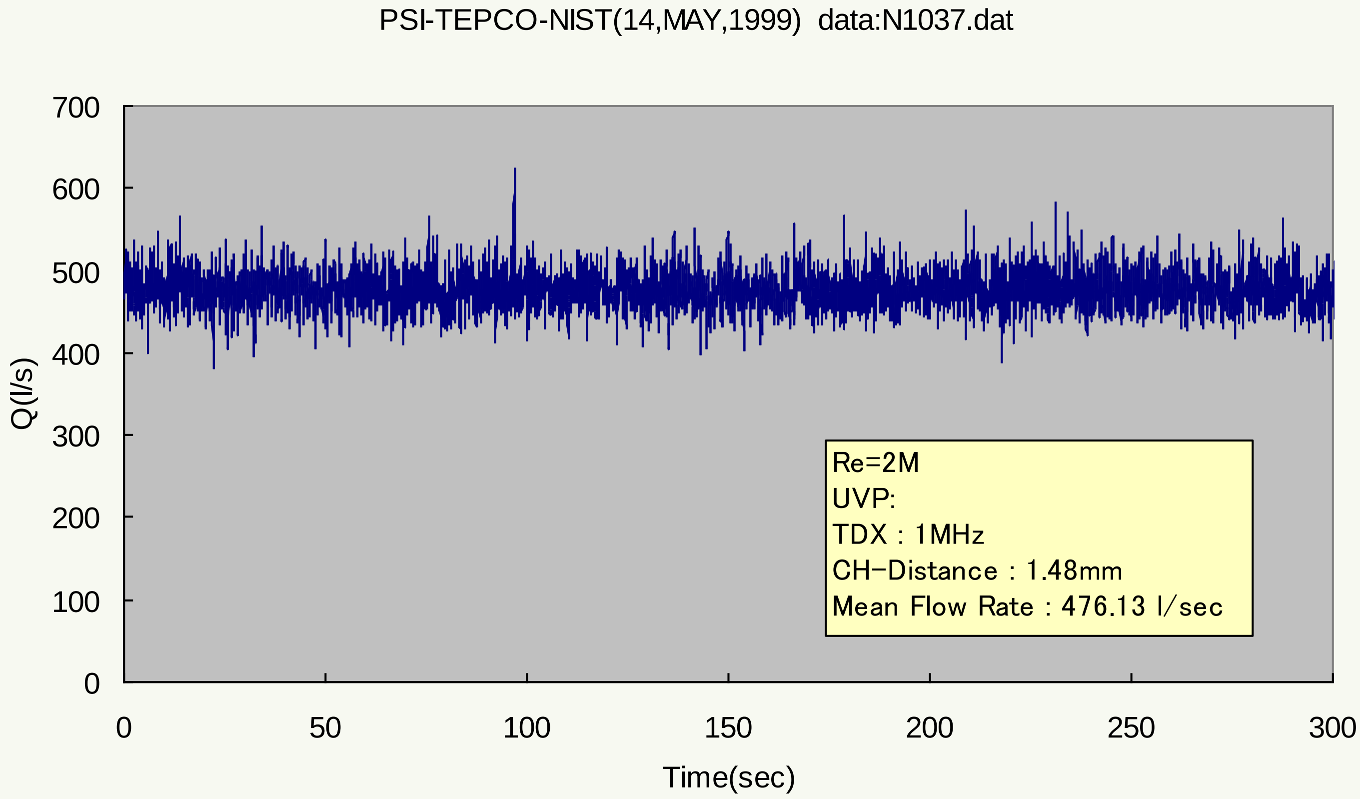
- NIST standard calibration system -



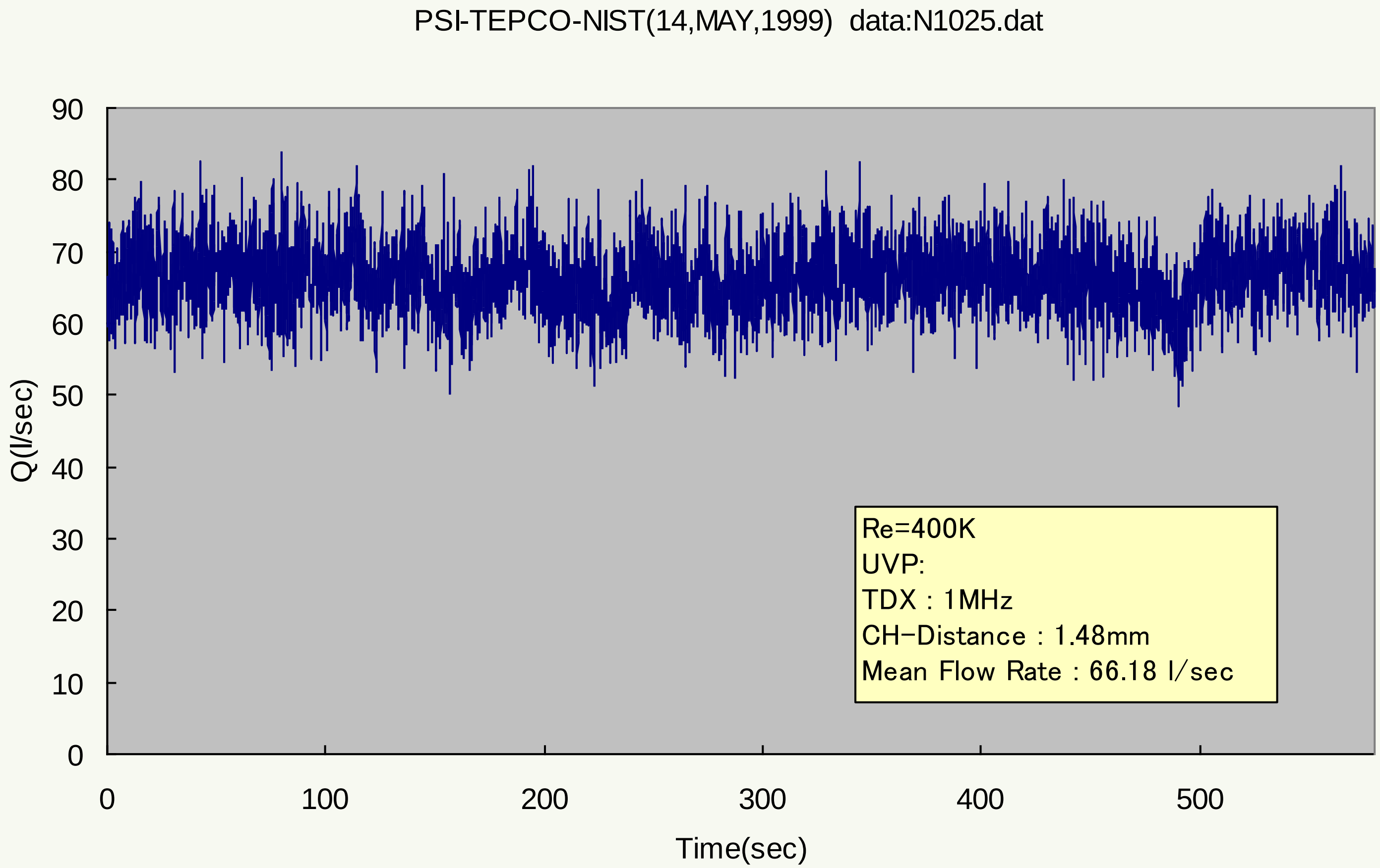
Picture of test section



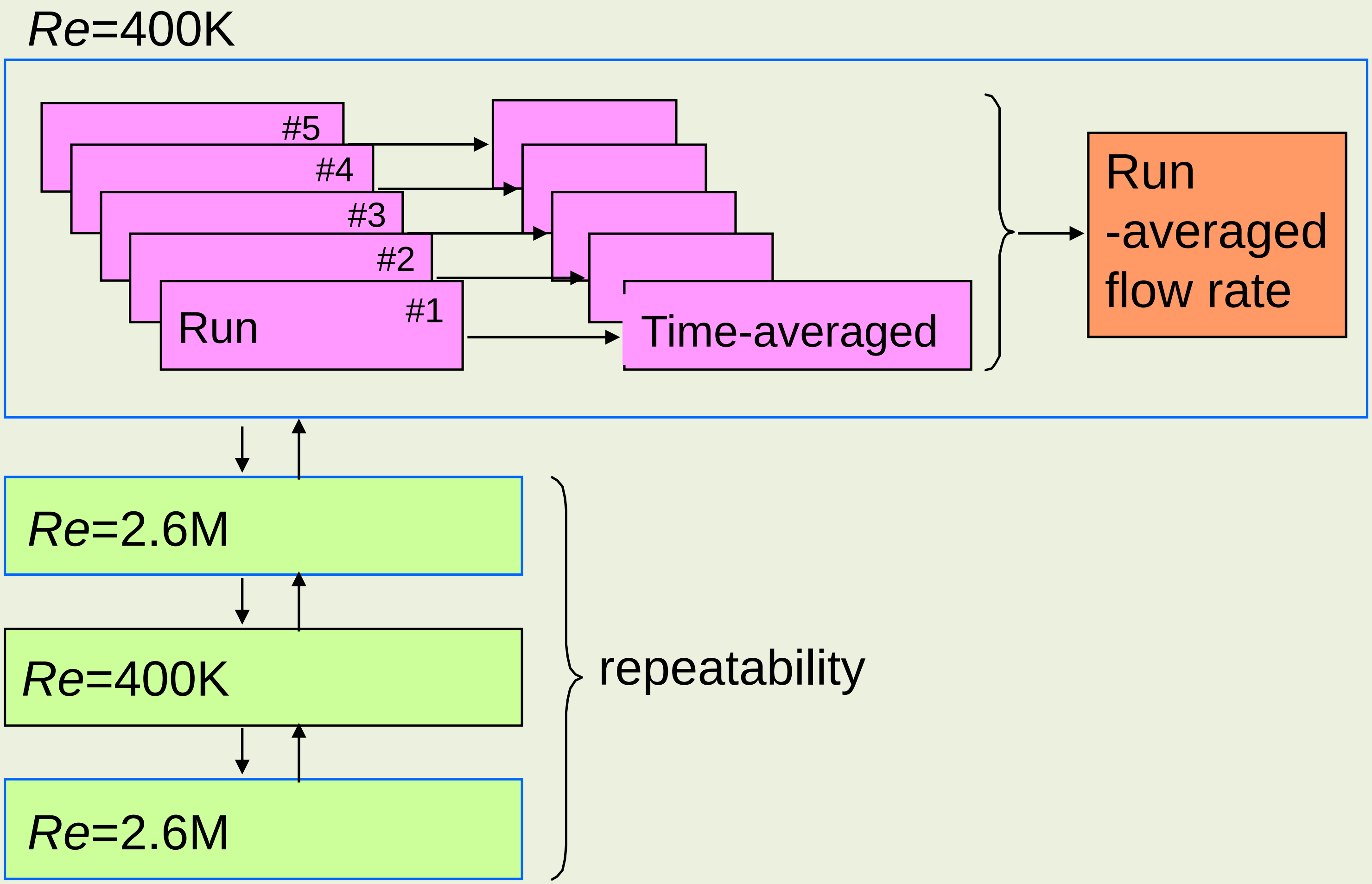
Mean velocity profile (*Re*=400K)



Transient flow rate (*Re*=2M)



Transient flow rate (*Re*=400K)



Experimental procedure

- NIST standard calibration system -

Flow Measurement

- Comparison with Weight Measurement -

Re=400K

fo=4MHz

	File	*UVP* Average	*(L/s)* Deviation	*Weight* GPM	*Re=400k* L/s	Difference	% error
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%**

Flow metering
Circular pipe

Principle

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

$\rightarrow$ High accuracy

$\rightarrow$ Transient flow rate

Flow rate

(circular pipe)

Measurement of velocity profile promises

- ✓ High accuracy
- ✓ No entry length
- ✓ No calibration
- ✓ No site effect

- ✓ Possible transient flow

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Multiphase Flow meter

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

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Graduate School of Engineering, Hokkaido University

Gas flow metering

Relevance to velocity profile in a pipe

IoT

Industrie 4.0

Flow sensor

Process Engineering

NPP $$P = \dot{Q} \bullet \Delta T$$

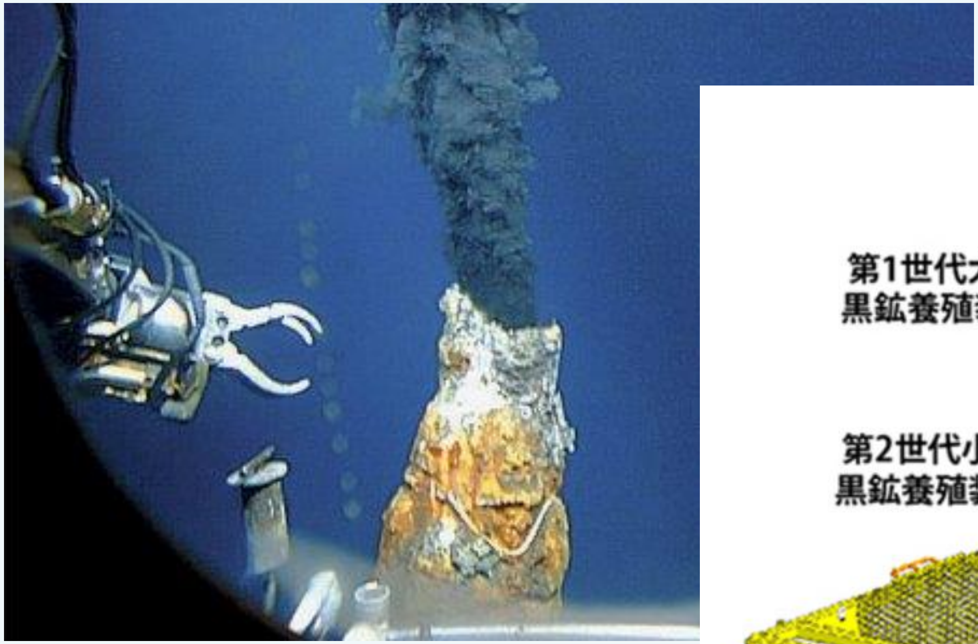
Mixing $$M = q_1 + q_2$$

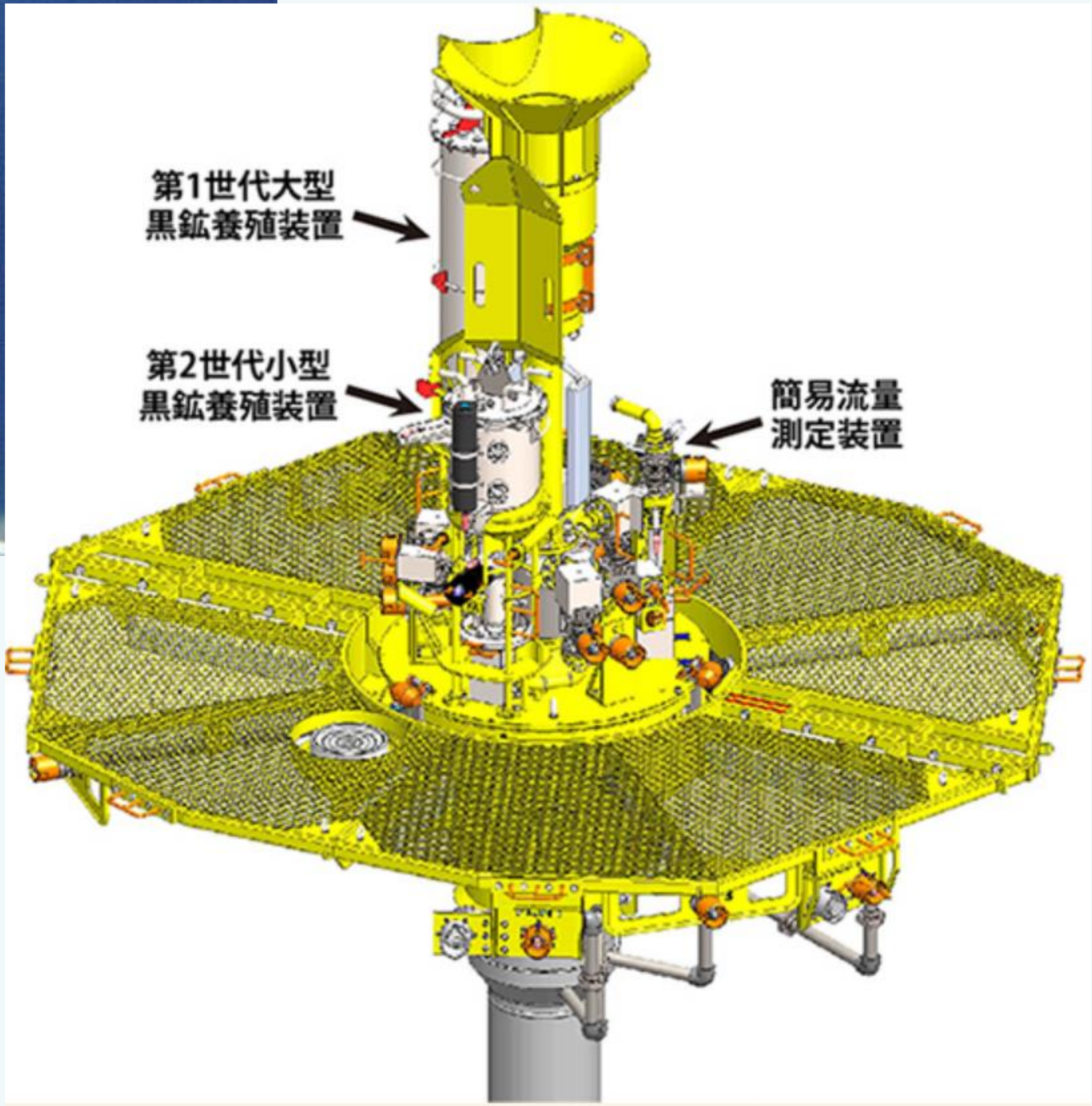
Flow rate

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

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

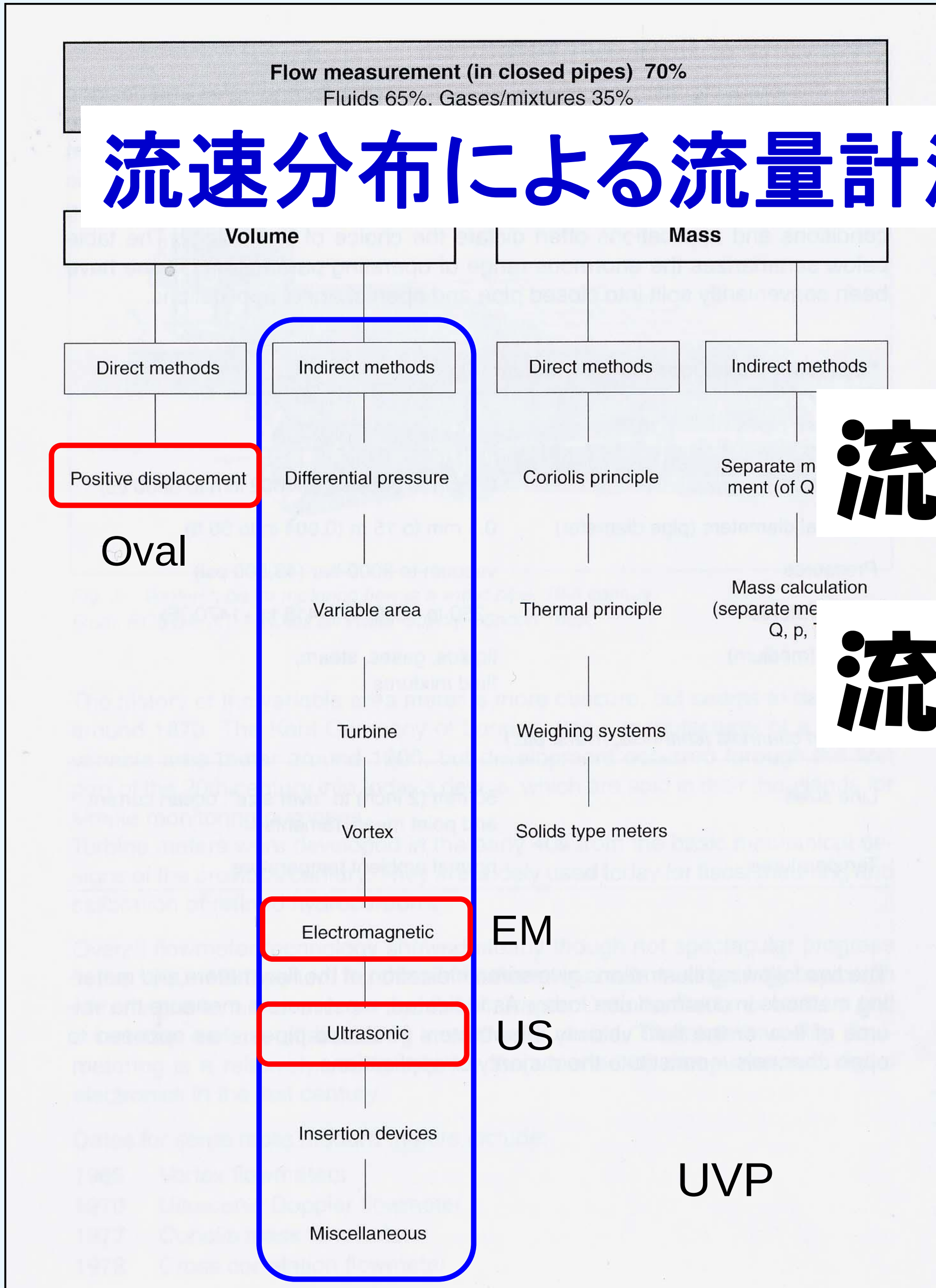
$(\boldsymbol{V_x},\ \boldsymbol{V_y},\ \boldsymbol{V_z})$
$(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$





第1世代大型
黒鉱養殖装置
第2世代小型
黒鉱養殖装置
簡易流量
測定装置

流速分布による流量計測 – A.Heronからの卒業



流量計測の革新

流量計　の革新

Fin