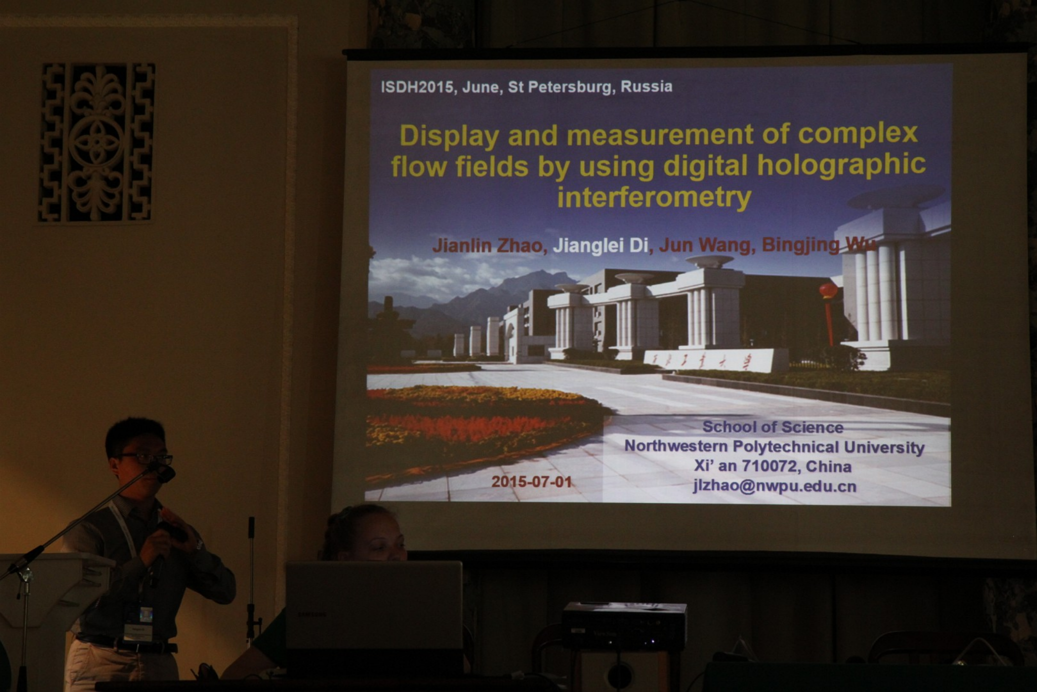
ISDH2015, June, St Petersburg, Russia
Display and measurement of complex flow fields by using digital holographic interferometry
Jianlin Zhao, Jianglei Di, Jun Wang, Bingjing Wu
School of Science
Northwestern Polytechnical University
Xi' an 710072, China
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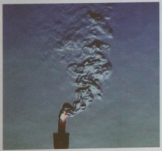
2015-07-01

Introduction

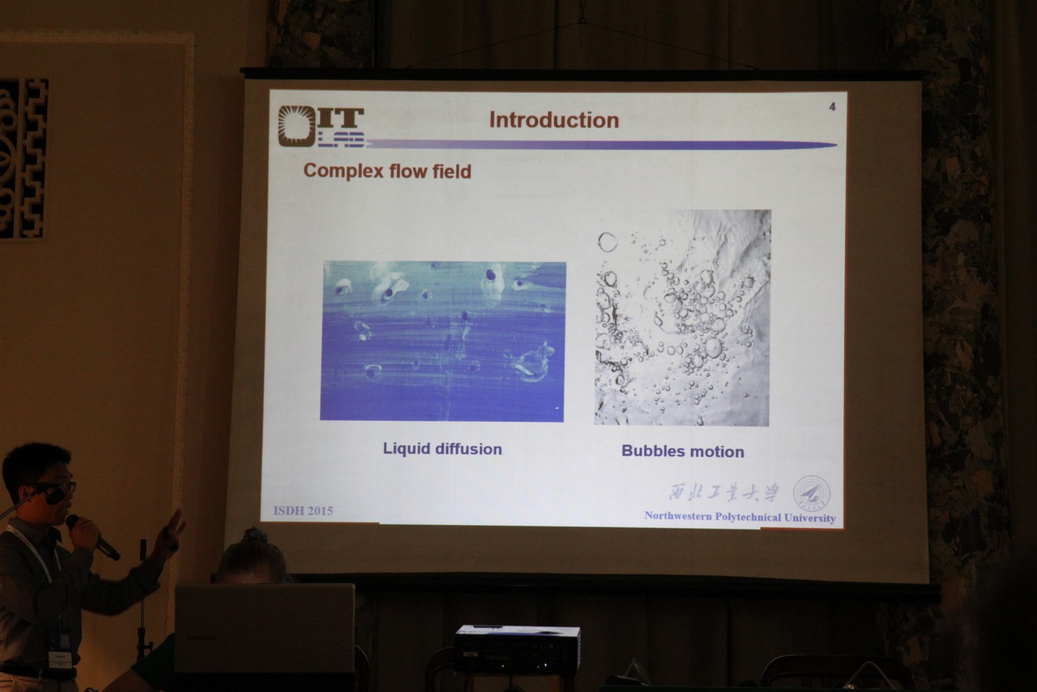
Complex flow field



Airflow and temperature induced by flame

Atmospheric Motion

Airflow in wind tunnel


4
Introduction
Complex flow field
Liquid diffusion
Bubbles motion
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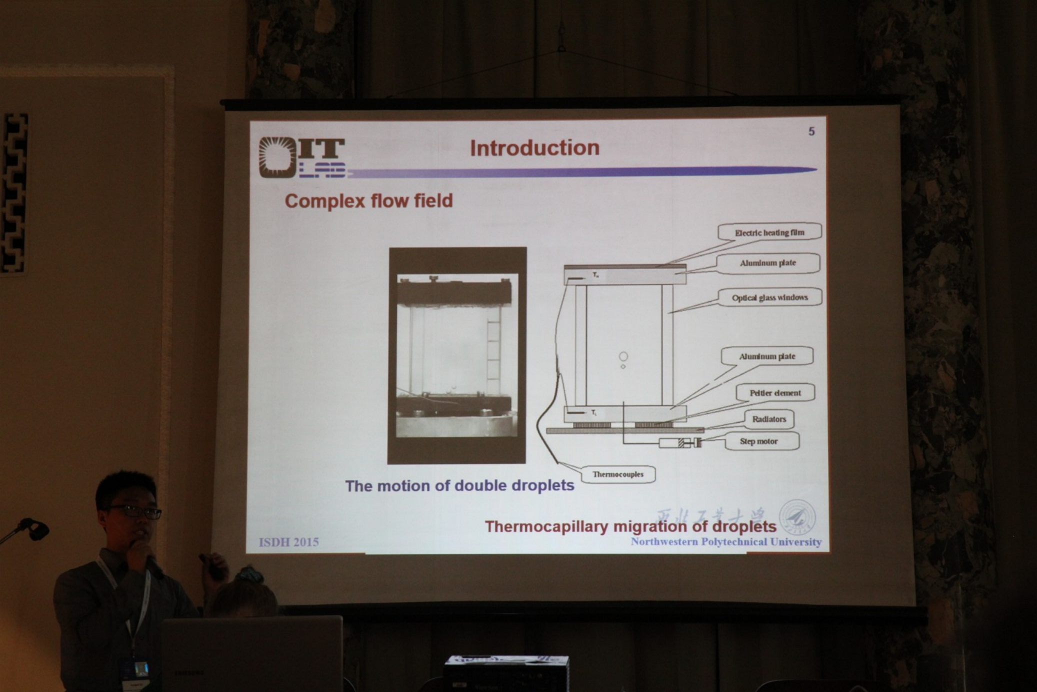
5
Introduction
Complex flow field
Electric heating film
Aluminum plate
Optical glass windows
Aluminum plate
Peltier element
Radiators
Step motor
Thermocouples
The motion of double droplets
Thermocapillary migration of droplets
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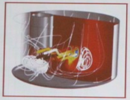
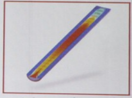
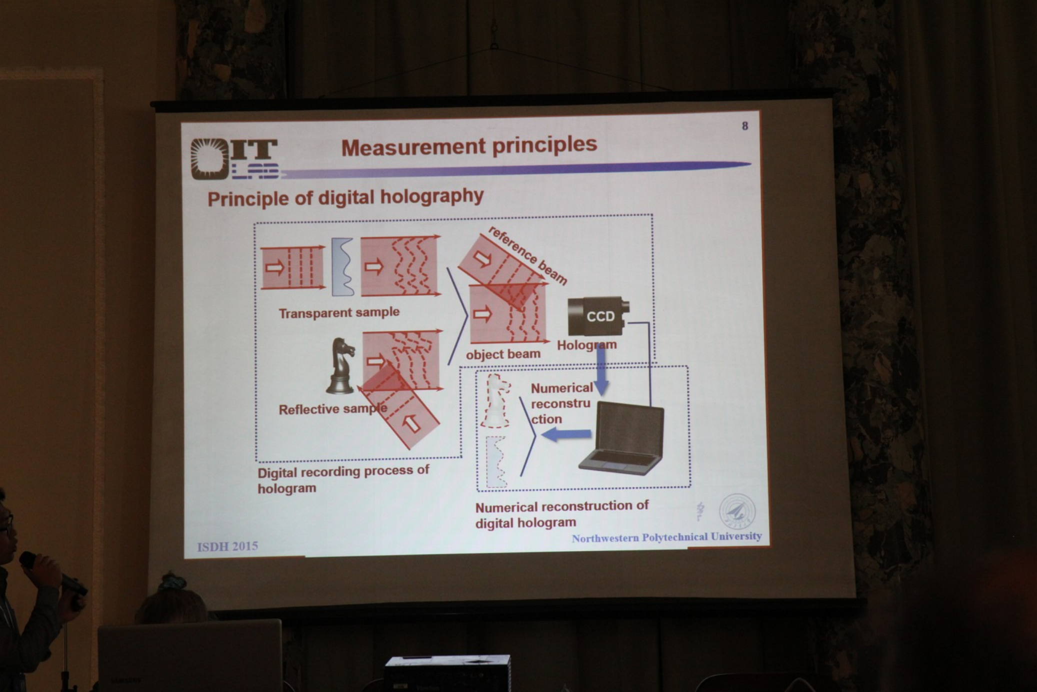
Introduction

How to achieve the visual, dynamical, non-destructive, high precision, full-field, quantitative measurement and display for complex flow field?






8
Measurement principles
Principle of digital holography
reference beam
CCD
Transparent sample
object beam
Hologram
Reflective sample
Numerical reconstru ction
Digital recording process of hologram
Numerical reconstruction of digital hologram
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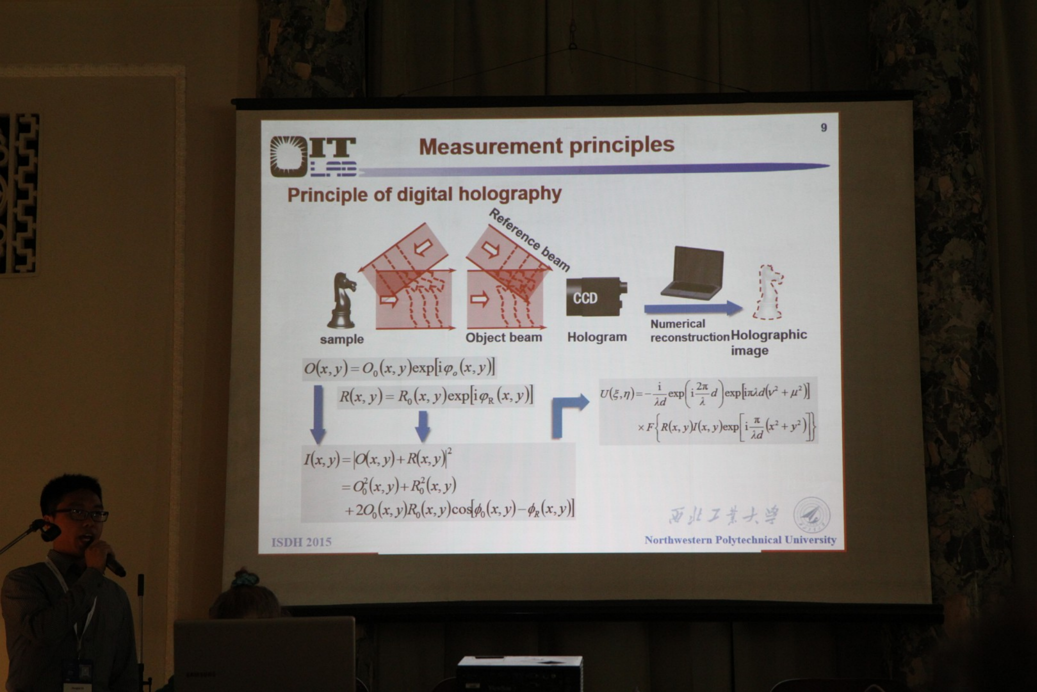
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Measurement principles
Principle of digital holography
Reference beam
sample
Object beam
CCD
Hologram
Numerical reconstruction
Holographic image
$O(x,y)=O_0(x,y)\exp[\mathrm{i}\varphi_o(x,y)]$
$R(x,y)=R_0(x,y)\exp[\mathrm{i}\varphi_R(x,y)]$
$I(x,y)=|O(x,y)+R(x,y)|^2 =O_0^2(x,y)+R_0^2(x,y) +2O_0(x,y)R_0(x,y)\cos[\phi_0(x,y)-\phi_R(x,y)]$
$U(\xi,\eta)=-\frac{\mathrm{i}}{\lambda d}\exp\left(\mathrm{i}\frac{2\pi}{\lambda}d\right)\exp[\mathrm{i}\pi\lambda d(v^2+\mu^2)] \times F\left\{R(x,y)I(x,y)\exp\left[\mathrm{i}\frac{\pi}{\lambda d}(x^2+y^2)\right]\right\}$
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Measurement principles

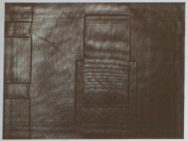
Principle of digital holography

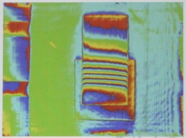
Holographic image intensity

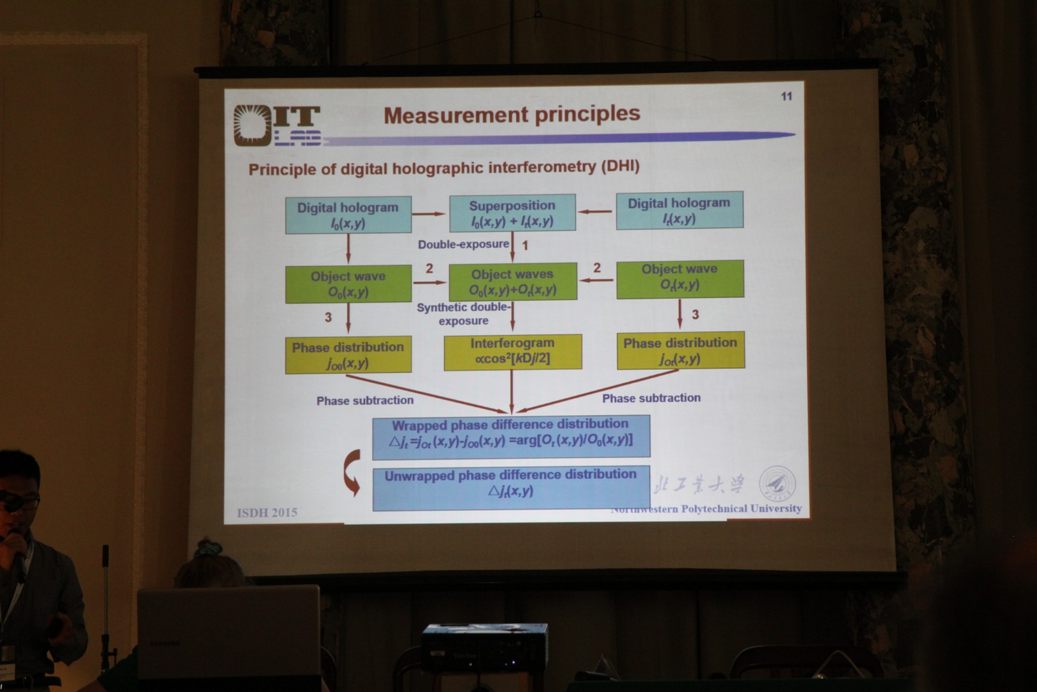
$$I(\xi,\eta)=\left|U(\xi,\eta)\right|^2$$

Holographic image phase

$$\varphi(\xi,\eta)=\arctan\frac{\mathrm{Im}\left[U(\xi,\eta)\right]}{\mathrm{Re}\left[U(\xi,\eta)\right]}$$






11
Measurement principles
Principle of digital holographic interferometry (DHI)
Digital hologram $I_0(x,y)$
Superposition $I_0(x,y) + I_t(x,y)$
Digital hologram $I_t(x,y)$
Double-exposure
1
2
2
Object wave $O_0(x,y)$
Object waves $O_0(x,y)+O_t(x,y)$
Object wave $O_t(x,y)$
3
Synthetic double-exposure
3
Phase distribution $j_{O0}(x,y)$
Interferogram $\propto\cos^2[kDj/2]$
Phase distribution $j_{Ot}(x,y)$
Phase subtraction
Phase subtraction
Wrapped phase difference distribution
$\triangle j_t = j_{Ot}(x,y) - j_{O0}(x,y) = \arg[O_t(x,y)/O_0(x,y)]$
Unwrapped phase difference distribution
$\triangle j_t(x,y)$
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Measurement principles

Relationship of phase difference and flow fields

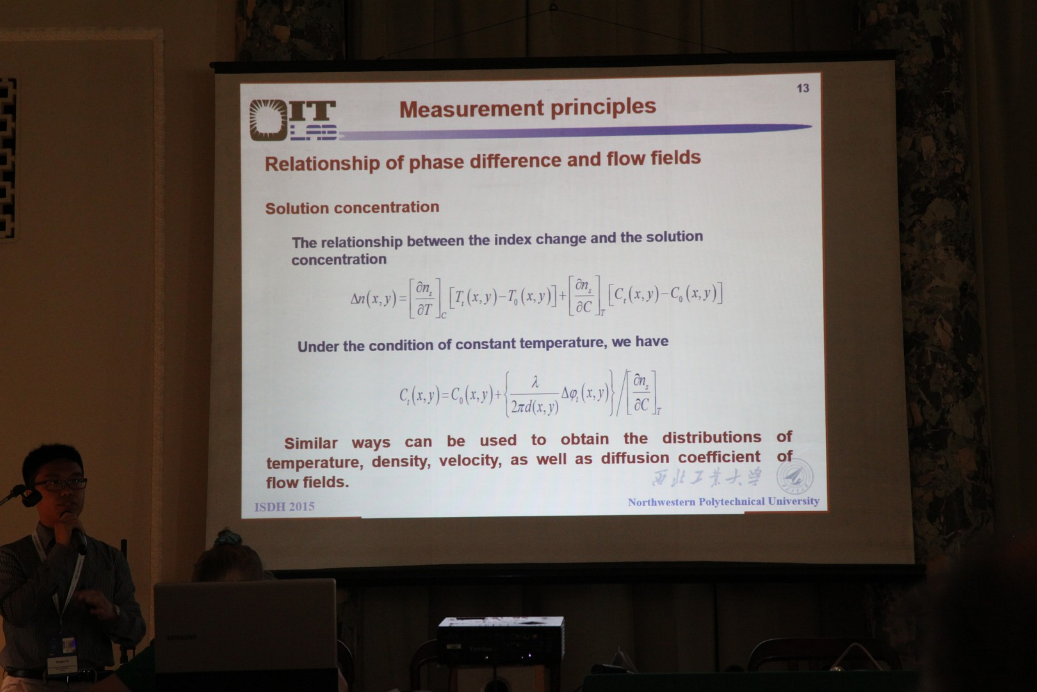
Distribution of refractive index change

Assuming that the index of flow field along the optical path (*z* axis) is uniform, the relationship between the index and phase changes can be expressed as

$$\Delta\varphi_t(x,y)=\frac{\lambda}{2\pi}\left(n_t(x,y)-n_0\right)d(x,y)=\frac{\lambda}{2\pi}\Delta n(x,y)d(x,y)$$

Then we can obtain the index change distribution

$$\Delta n(x,y)=\frac{2\pi}{\lambda}\cdot\frac{\Delta\varphi_t(x,y)}{d(x,y)}$$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Measurement principles
Relationship of phase difference and flow fields
Solution concentration
The relationship between the index change and the solution concentration
$$\Delta n(x,y)=\left[\frac{\partial n_s}{\partial T}\right]_C\left[T_t(x,y)-T_0(x,y)\right]+\left[\frac{\partial n_s}{\partial C}\right]_T\left[C_t(x,y)-C_0(x,y)\right]$$
Under the condition of constant temperature, we have
$$C_t(x,y)=C_0(x,y)+\left\{\frac{\lambda}{2\pi d(x,y)}\Delta\varphi_t(x,y)\right\}\Big/\left[\frac{\partial n_s}{\partial C}\right]_T$$
Similar ways can be used to obtain the distributions of temperature, density, velocity, as well as diffusion coefficient of flow fields.
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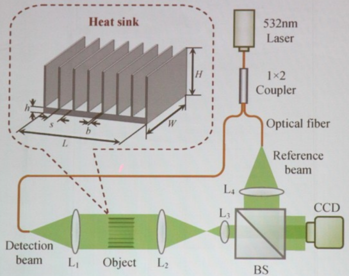
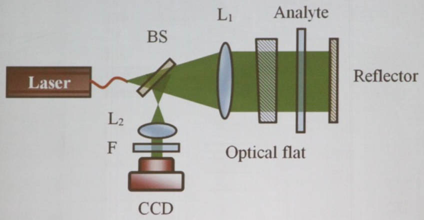
Applications

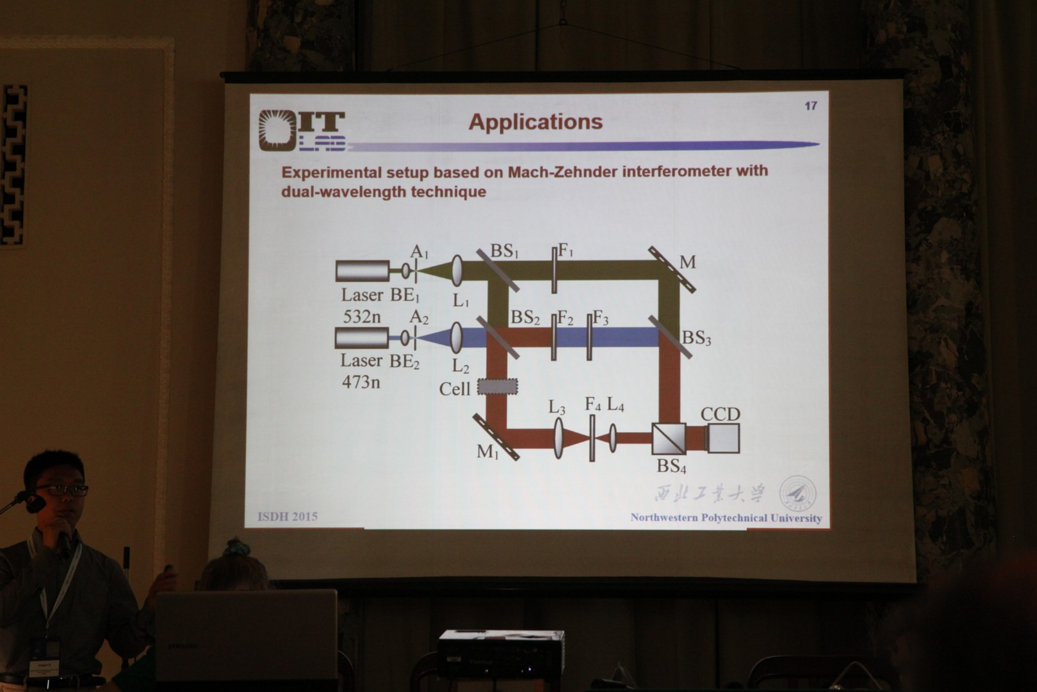
Experimental setup based on Mach-Zehnder interferometer



Applications

Experimental setup based on Fizeau interferometer





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Applications
Experimental setup based on Mach-Zehnder interferometer with dual-wavelength technique
A1
BS1
F1
M
Laser BE1
L1
532n
A2
BS2
F2
F3
BS3
Laser BE2
L2
473n
Cell
L3
F4 L4
CCD
M1
BS4
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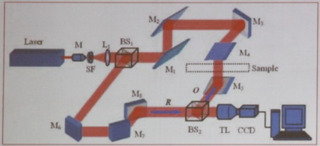
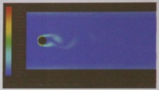
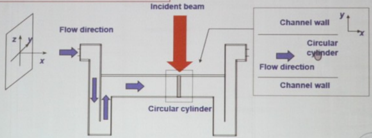
Application:1

Application 1: Karman vortex street in water flow field





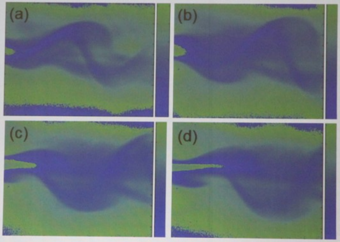


Sample for Karman vortex street generation

W. Sun, J. Zhao, J. Di, et al, *Opt. Express 2009, 17*

Application 1

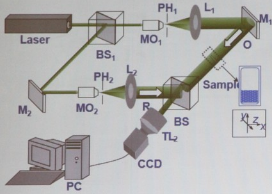
Application 1: Phase difference distribution of Karman vortex street



W. Sun, J. Zhao, J. Di, et al, *Opt. Express* 2009, 17

Application 2

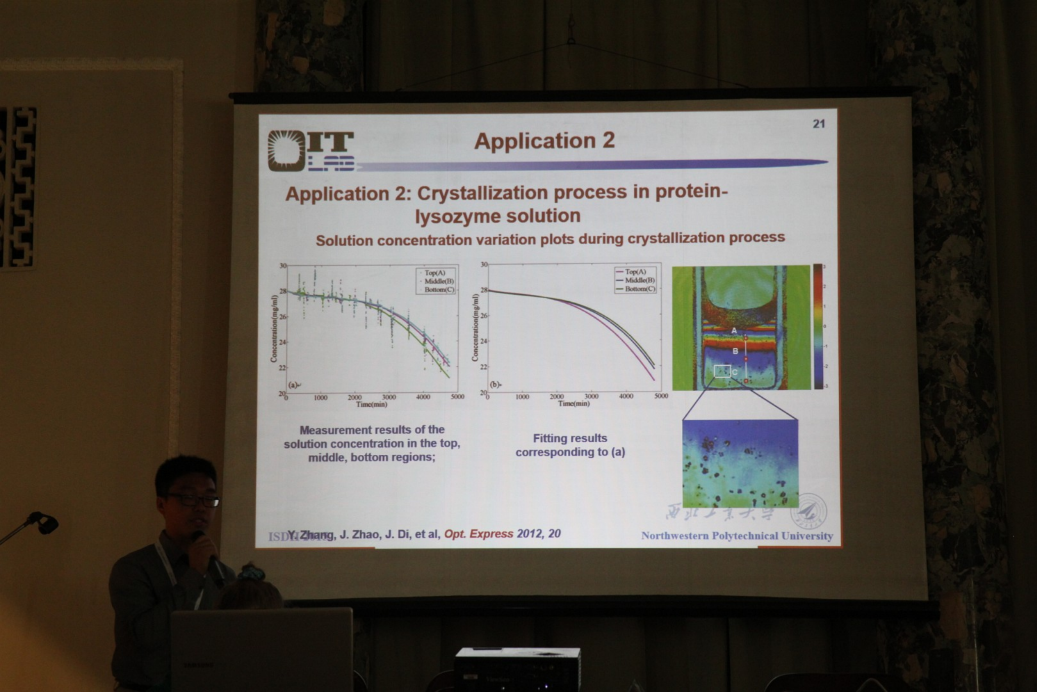
Application 2: Crystallization process in protein-lysozyme solution



Dynamic wrapped phase difference map (0~4750min)

Solution sample:
1:1 mixing solution of lysozyme (28mg/ml) and NaCl (35mg/ml)

Y. Zhang, J. Zhao, J. Di, et al, *Opt. Express* 2012, 20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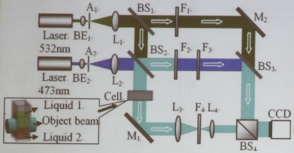
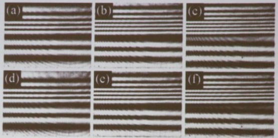
Application 2
Application 2: Crystallization process in protein-lysozyme solution
Solution concentration variation plots during crystallization process
Top(A)
Middle(B)
Bottom(C)
Concentration(mg/ml)
Time(min)
(a)
(b)
A
B
C
Measurement results of the solution concentration in the top, middle, bottom regions;
Fitting results corresponding to (a)
Y. Zhang, J. Zhao, J. Di, et al, Opt. Express 2012, 20
Northwestern Polytechnical University

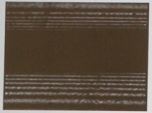
Application 3

Application 3: Liquid diffusion

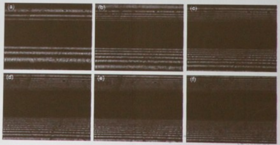




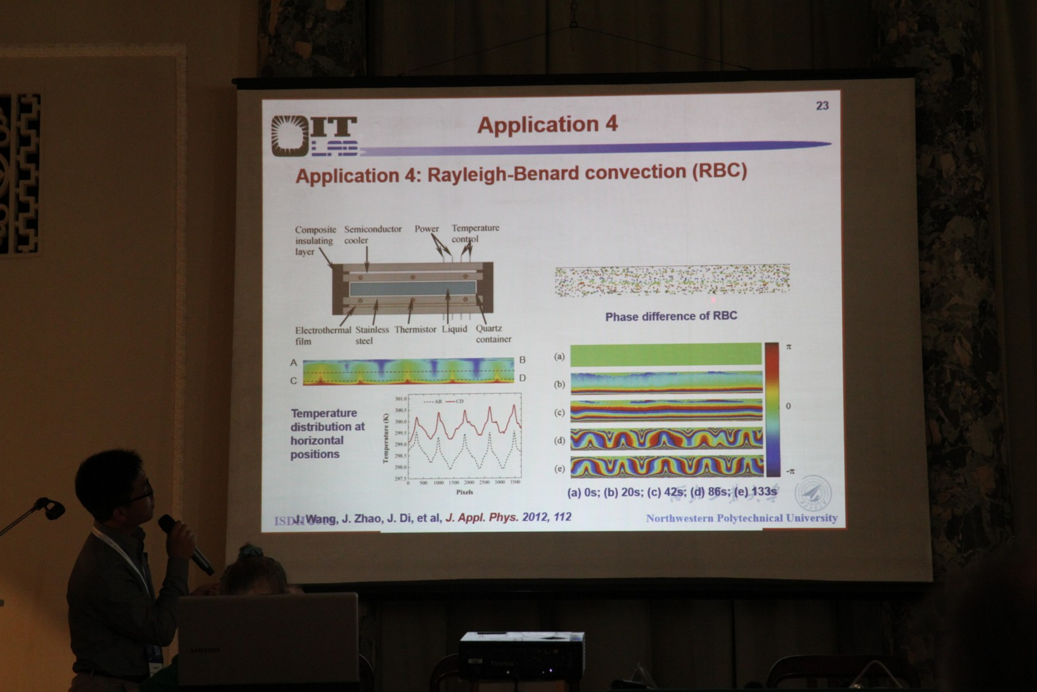
Ternary diffusion process in liquids



Diffusion process between water and alcohol



J. Wang, J. Zhao, C. Qin, et al, *Opt. Lett.* 2012, 37



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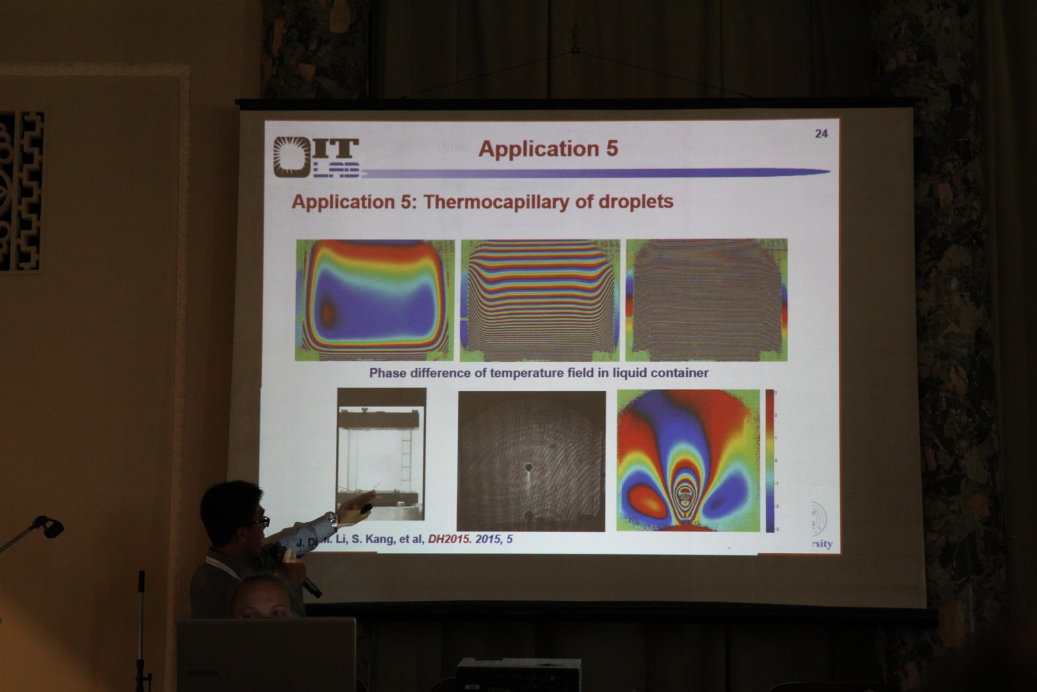
Application 4
Application 4: Rayleigh-Benard convection (RBC)
Composite insulating layer
Semiconductor cooler
Power
Temperature control
Electrothermal film
Stainless steel
Thermistor
Liquid
Quartz container
A
B
C
D
Temperature distribution at horizontal positions
Temperature (K)
Pixels
AB
CD
Phase difference of RBC
(a)
(b)
(c)
(d)
(e)
π
0
-π
(a) 0s; (b) 20s; (c) 42s; (d) 86s; (e) 133s
J. Wang, J. Zhao, J. Di, et al, J. Appl. Phys. 2012, 112
Northwestern Polytechnical University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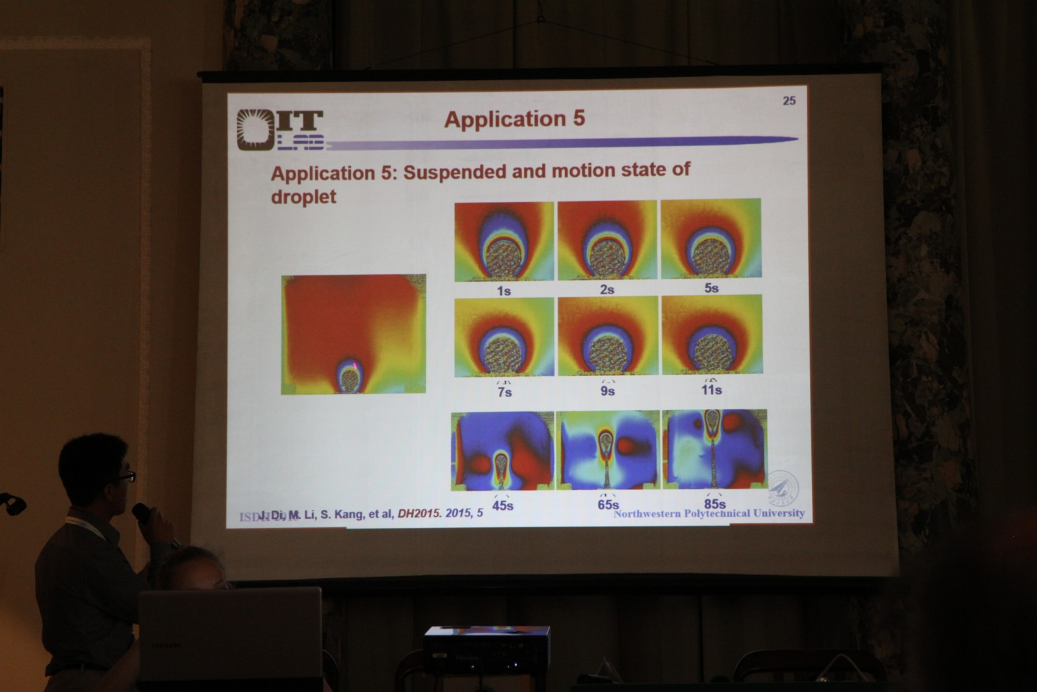
Application 5
Application 5: Thermocapillary of droplets
Phase difference of temperature field in liquid container
M. Li, S. Kang, et al, DH2015. 2015, 5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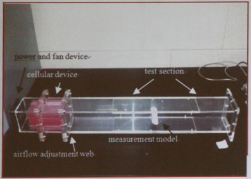
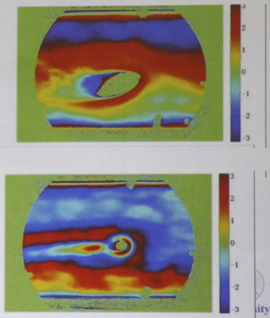
Application 5
Application 5: Suspended and motion state of droplet
1s
2s
5s
7s
9s
11s
45s
65s
85s
J. Di, M. Li, S. Kang, et al, DH2015. 2015, 5
Northwestern Polytechnical University

Application 6

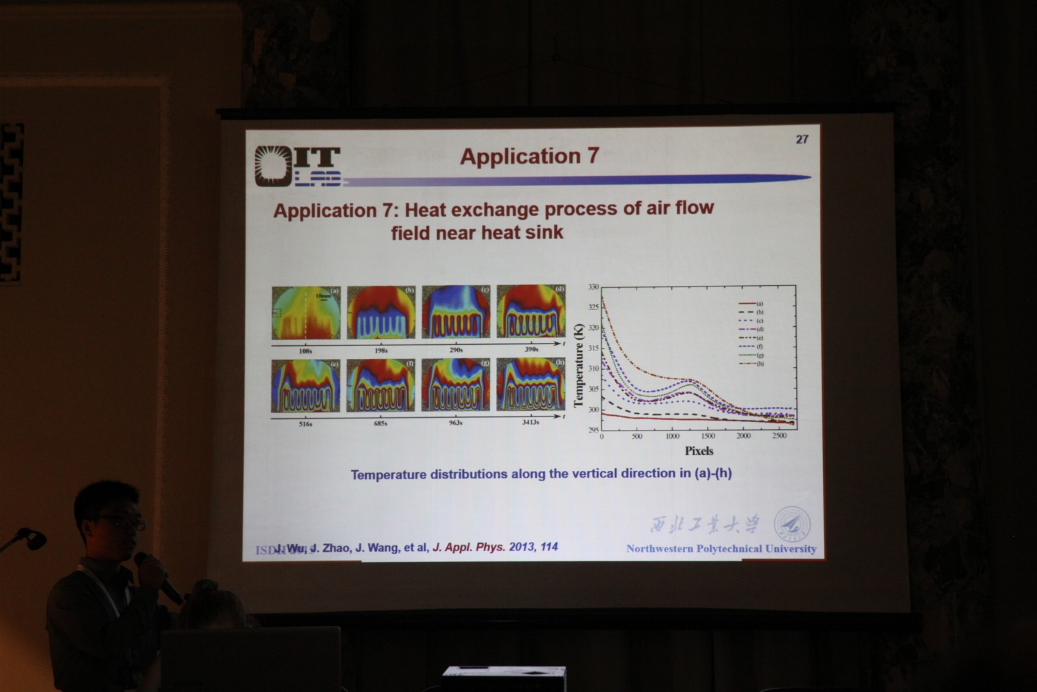
Application 6: Air flow in wind tunnel



Wind tunnel model



J. Di, J. Wang, B. Wu, et al, *Proc. SPIE 2013*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Application 7
Application 7: Heat exchange process of air flow field near heat sink
108s
198s
290s
390s
516s
685s
963s
3413s
Temperature (K)
Pixels
Temperature distributions along the vertical direction in (a)-(h)
J. Wu, J. Zhao, J. Wang, et al, J. Appl. Phys. 2013, 114
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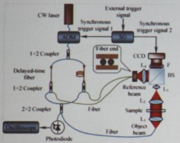
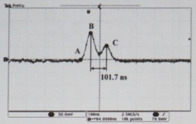
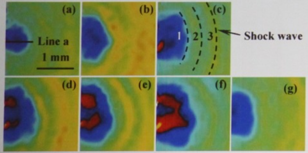
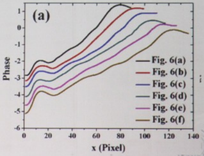
Application 8

Application 8: Shockwave field





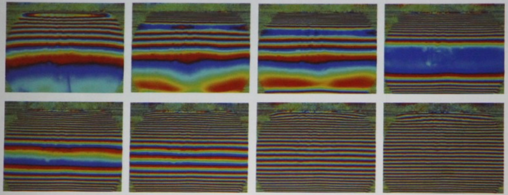


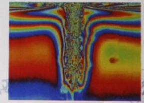


 J. Wang, J. Zhao, J. Di, et al, *Opt. and Laser in Eng.* 2015, 67

Application 9

Application 9: Unstable reaction-diffusion process



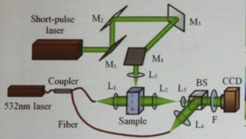


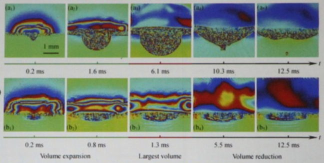
J. Wang, J. Zhao, J. Di, et al, *Opt. and Laser in Eng. 2014, 57*

Application 10

Application 10: Laser ablation on the surfaces of liquid

Phase difference distributions of the ablation region

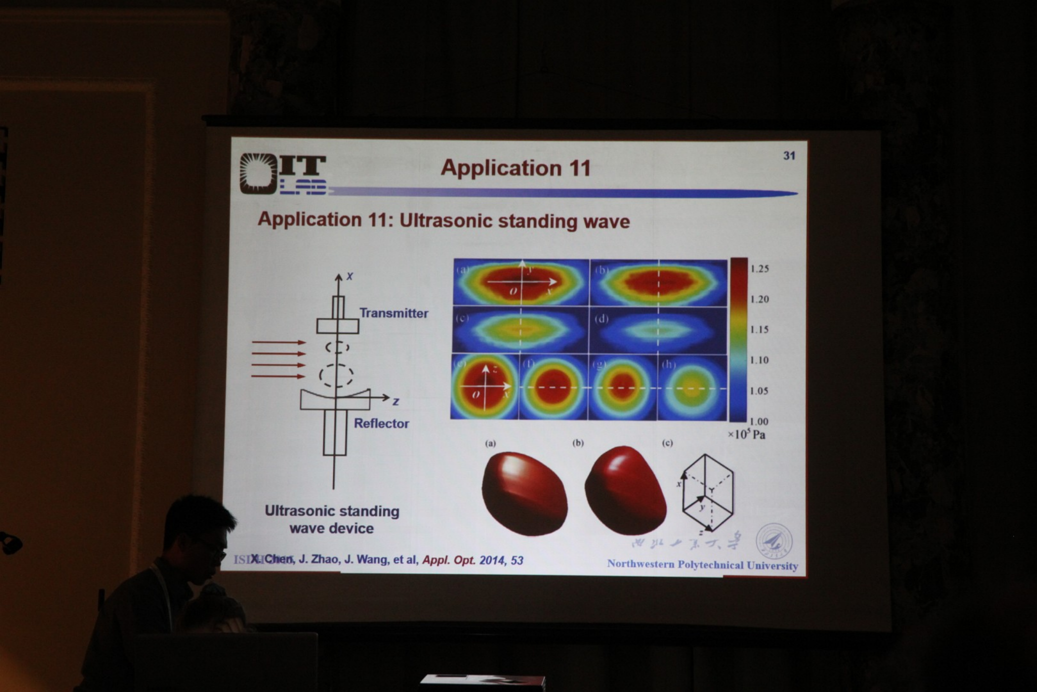




(a) Deionized water using 470 mJ energy; (b) glycerin using 470 mJ energy.

From the phase change between the two adjacent pixels in saltation process, the boundaries of cavity and jet can be detected.

J. Wang, J. Zhao, J. Di, et al, *J. Appl. Phys. 2014, 115*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Application 11
Application 11: Ultrasonic standing wave
x
Transmitter
z
Reflector
Ultrasonic standing wave device
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
1.25
1.20
1.15
1.10
1.05
1.00
×10^5 Pa
(a)
(b)
(c)
X. Chen, J. Zhao, J. Wang, et al, Appl. Opt. 2014, 53
Northwestern Polytechnical University

Summary

- Several applications of digital holographic interferometry in display and measurement of complex flow fields are presented.
- Related experiment results with specially designed setups during the dynamic evolution processes of flow fields are shown.
- Digital holographic interferometry is an effective tool.