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3rd International Conference and Exhibition on
Mechanical & Aerospace Engineering
San Francisco, USA. October 05-07, 2015

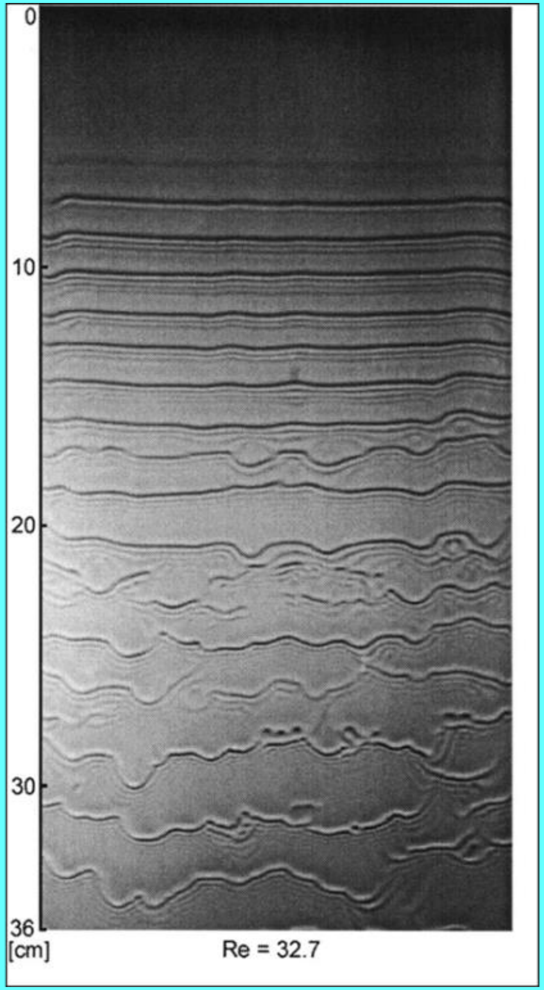
NONLINEAR WAVES AND TRANSFER PROCESSES IN LIQUID FILM FLOW

S. Alekseenko

*Institute of Thermophysics,
Novosibirsk, Russia*

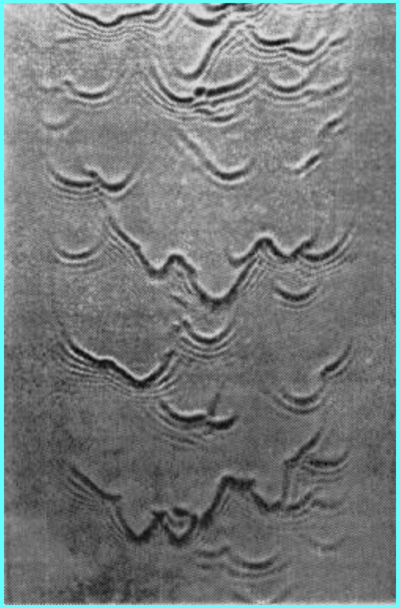
Natural waves on a falling film

Wave evolution

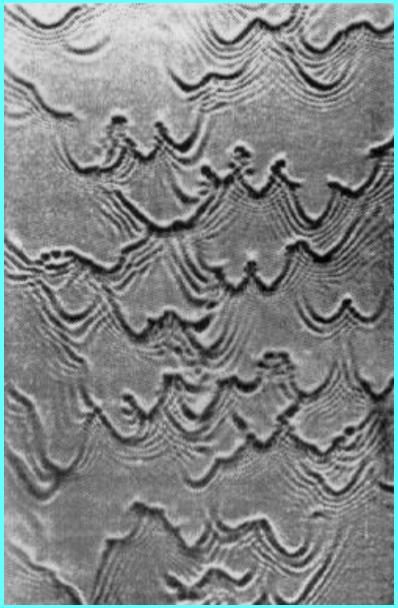


Park, Nosoko: 2003

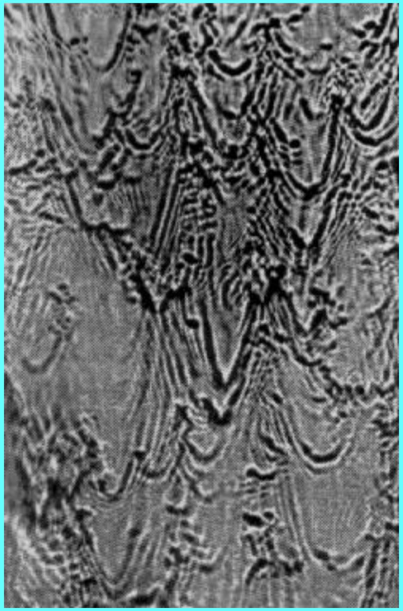
Waves at a large distance from the inlet: effect of Reynolds number, Re



Re = 15



Re = 45

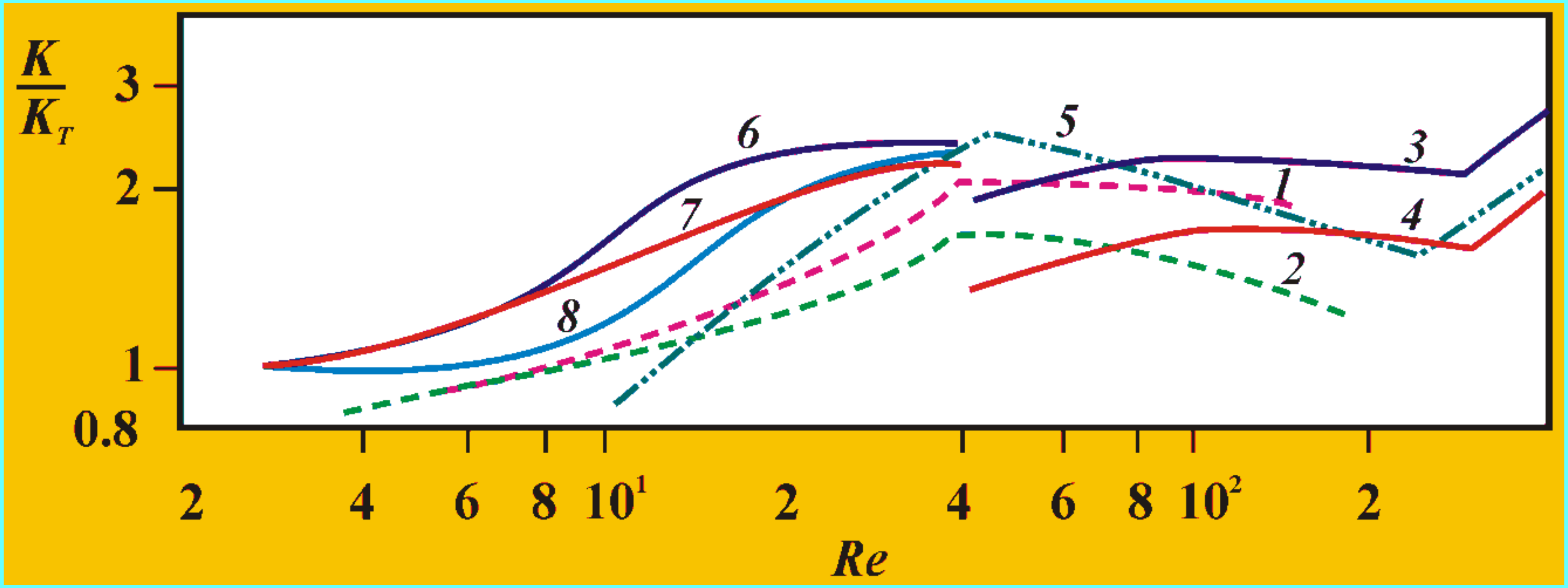


Re = 260

Residual layer: Re < 5

Alekseenko, Nakoryakov, Pokusaev: Wave Flow of Liquid Films, 1994

Wave effect on transfer processes



Relative mass transfer coefficient depending on Reynolds number *Re*.

CO_2 absorption by falling liquid film.

K_T - mass transfer in smooth film.

1 – 8 – various experiments

Wave effect up to **170%!**

Contents

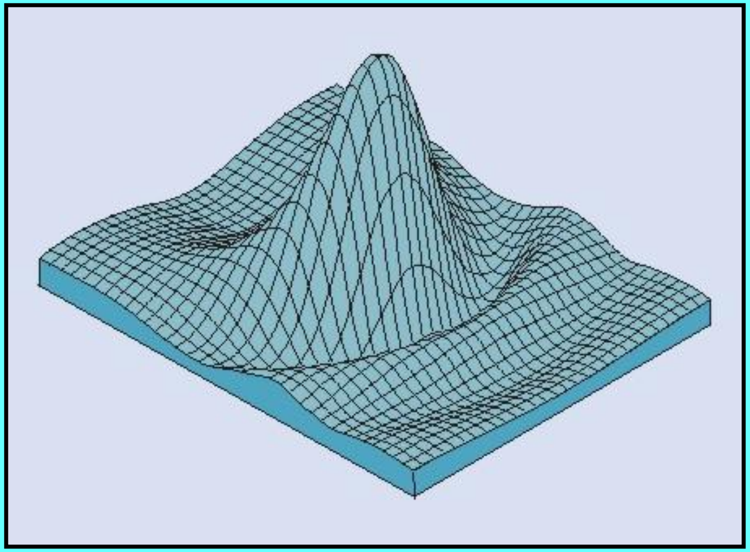
1. 3-D solitary waves in falling liquid film
2. Wavy rivulet flow
3. Instabilities in annular two-phase flow
4. Transport phenomena:

   Wave effect on condensation

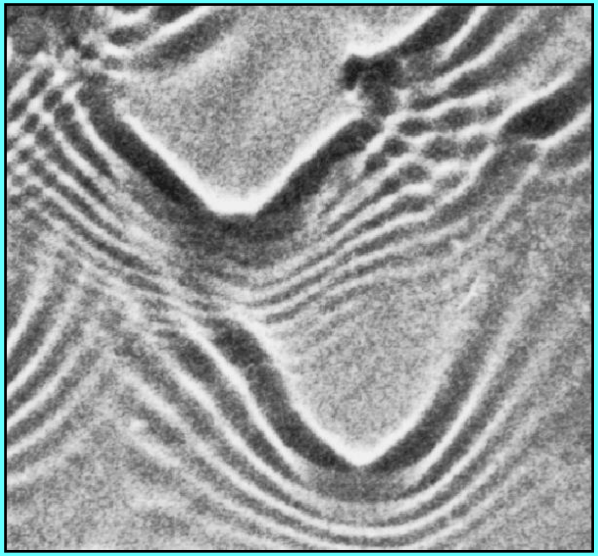
1. 3-D SOLITARY WAVES IN FALLING FILM

Equation for long 3-D waves at *Re* ~ 1

$$\frac{\partial H}{\partial t} + 3\frac{\partial H}{\partial \boldsymbol{x}} + 6H\frac{\partial H}{\partial \boldsymbol{x}} + \boldsymbol{Re}\frac{\partial^2 H}{\partial \boldsymbol{x}^2} + \boldsymbol{W}\left(\frac{\partial^2}{\partial \boldsymbol{x}^2} + \frac{\partial^2}{\partial \boldsymbol{y}^2}\right)^2 \boldsymbol{H} = 0$$



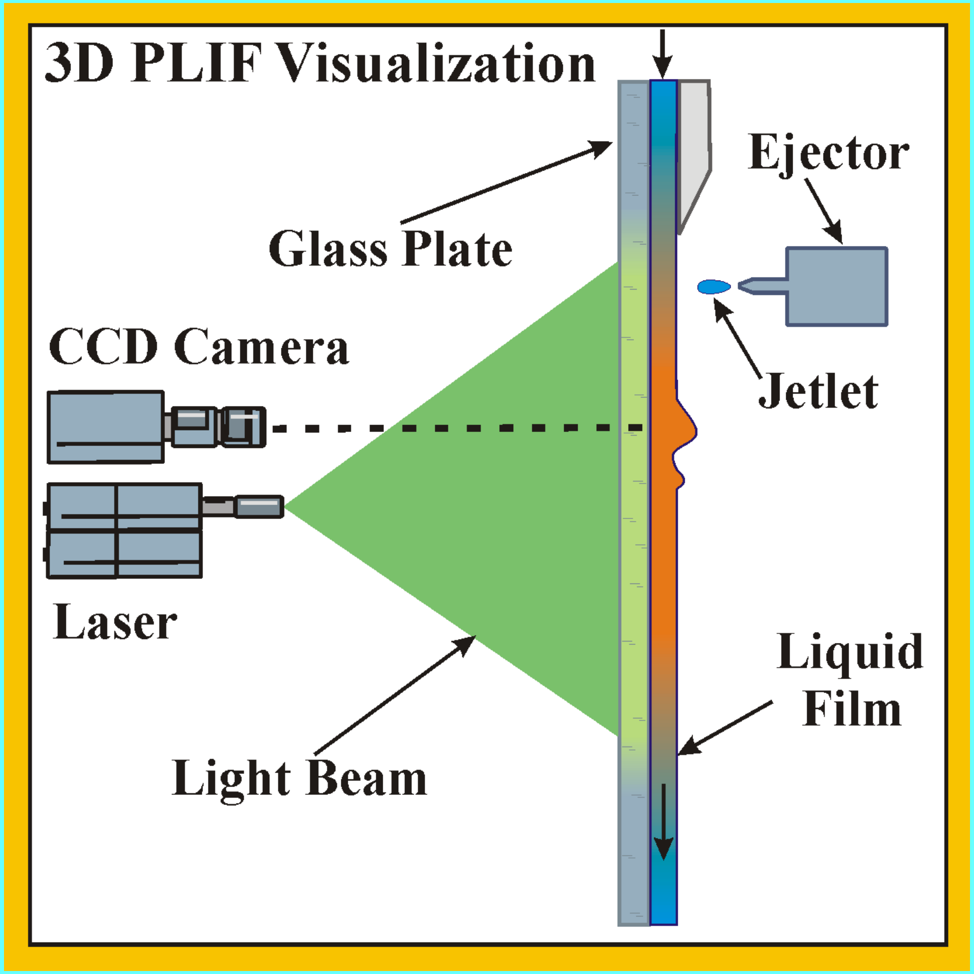
Solitary statinary 3-D wave at *Re* ~ 1
(*Petviashvili, Tsvelodub, 1978*)



Solitary 3-D wave
(experiment by *Alekseenko et al*)

The three-dimensionality is found only in the capillary term

Generation of solitary waves

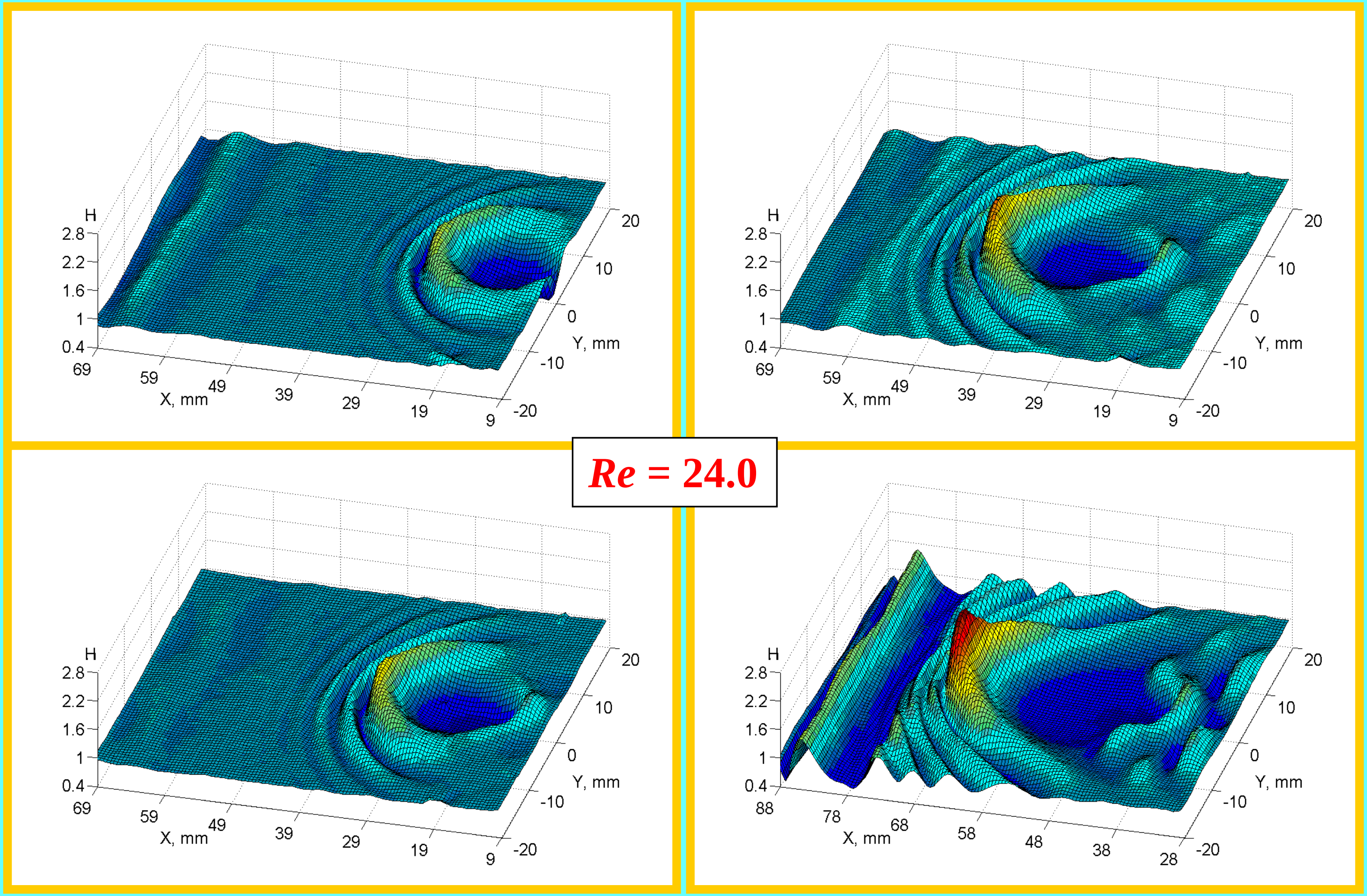


Measurement of 3-D distribution of liquid film thickness with Planar Laser Induced Fluorescence method (PLIF):
Doubled NdYAG Laser (532nm);
CCD Camera "Kodak Megaplus ES1.0" in double frame mode;
Fluorescent dye – Rhodamine 6G , 0.01% wt.

Initial solitary perturbation was produced due to interaction of the jetlet with a smooth film surface.

Alekseenko, Antipin, Guzanov, Markovich, Kharlamov: Phys. Fluids, 2005

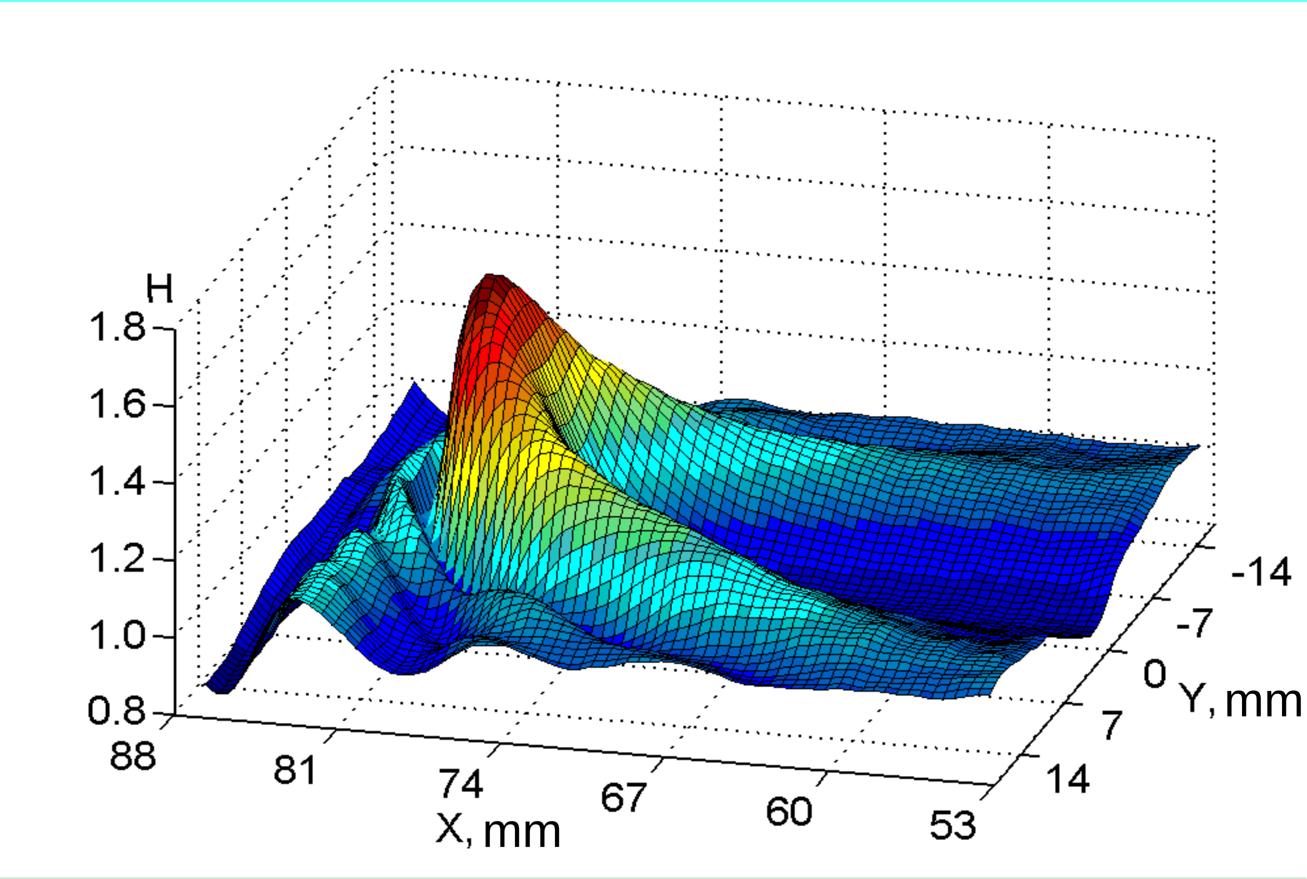
Evolution of initial solitary perturbation

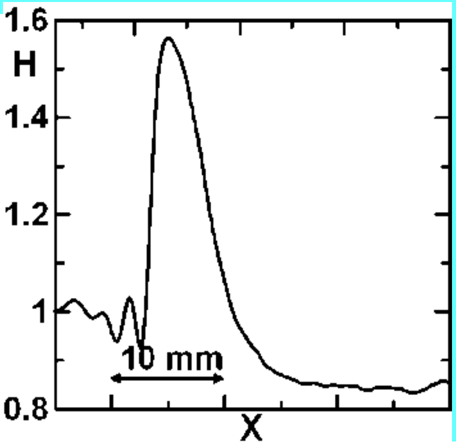


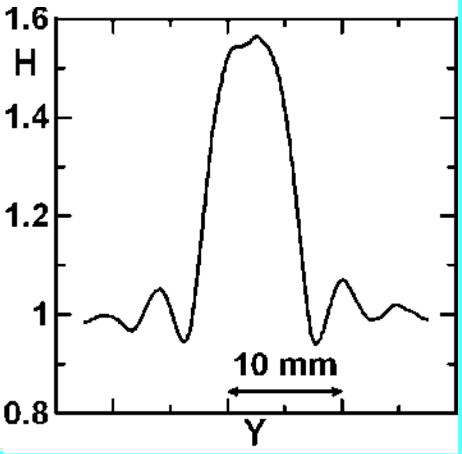
***Re* = 24.0**

Alekseenko, Antipin, Guzanov, Markovich, Kharlamov: ***Phys. Fluids, 2005***

Shape of 3-D stationary solitary wave





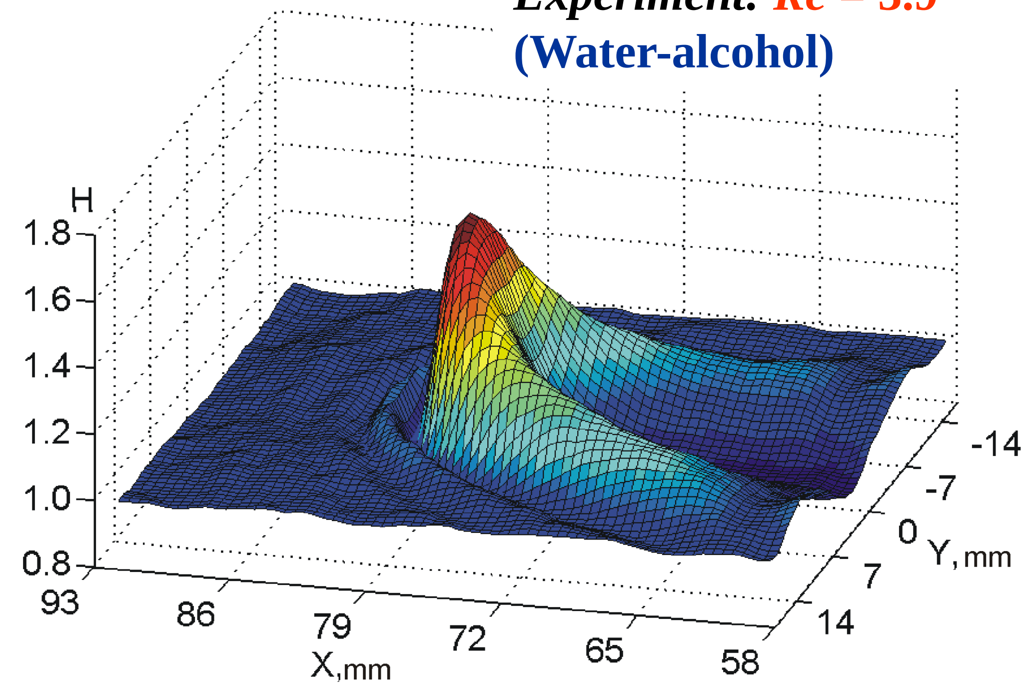


Re = 4.7 **(Water-alcohol)**

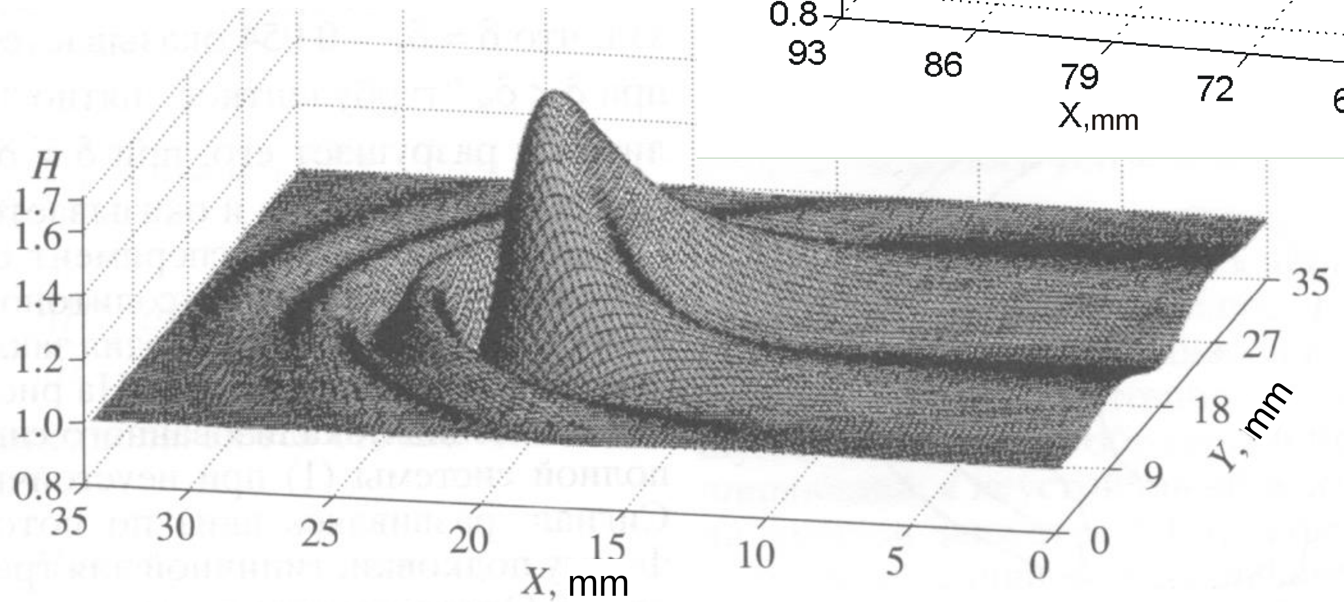
Alekseenko, Antipin, Guzanov, Markovich, Kharlamov: Phys. Fluids, 2005

Shape of 3-D stationary solitary wave

Experiment: ***Re*** **= 3.9**
(Water-alcohol)

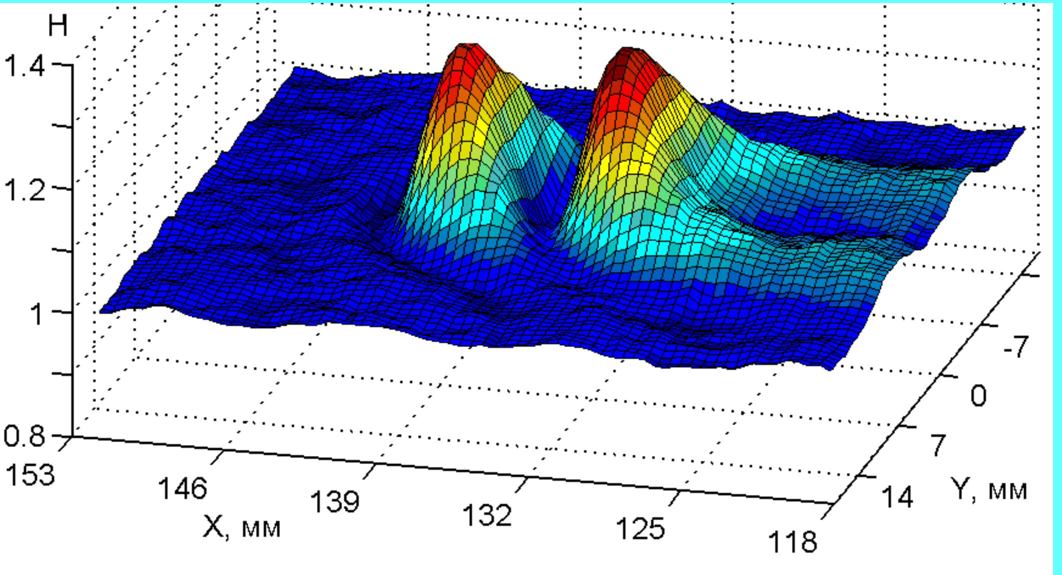


Theory: ***Demekhin et al (2007)***
(Integral equations)

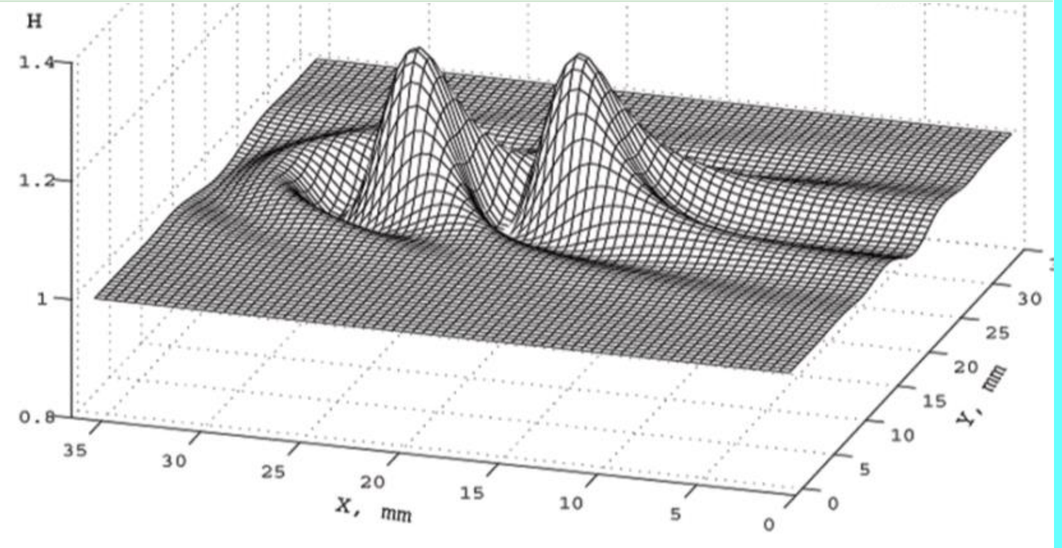


Double 3-D stationary solitary wave

Experiment:
Re = 1.9



Theory:
Demekhin et al (2007)
(Integral equations)



Conclusion

3D stationary solitary waves are found experimentally in liquid film flow. They were predicted previously on the basis of theoretical simulation.

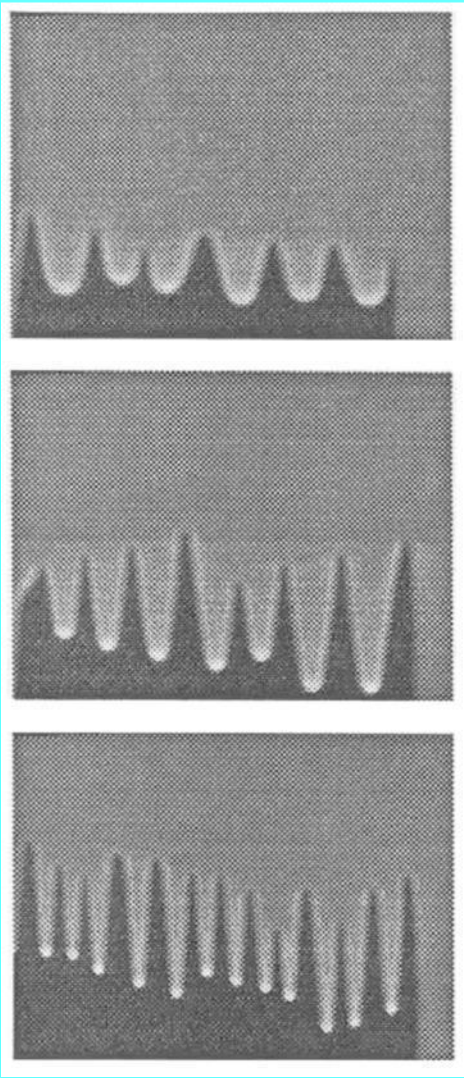
Such type of a wave is considered to be a fundamental element of wavy liquid film flows.

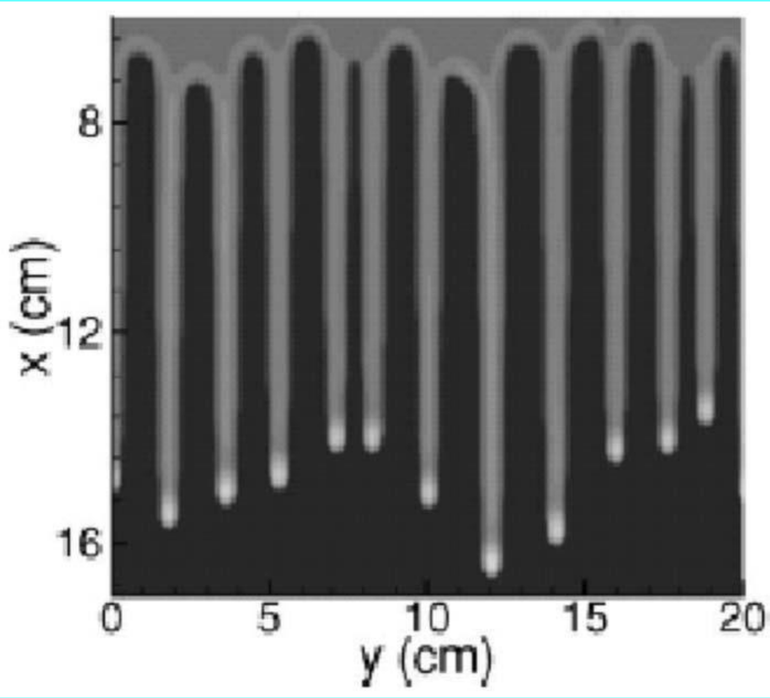
2. WAVY RIVULET FLOW

Rivulets on a solid wall

Rivulet formation at breakdown of the liquid film front

Single rivulet

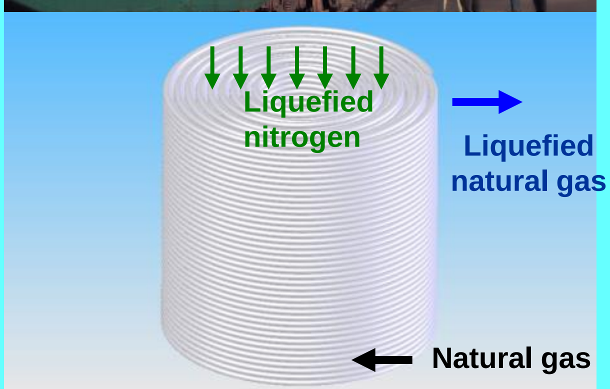


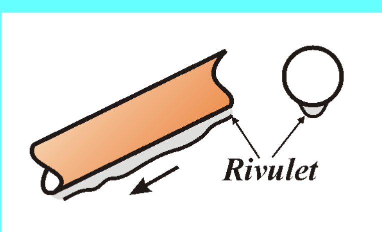


Viscous film flow of water-glycerol solution (Johnson et al. 1999)

Rivulet on inclined cylinder and regular packing

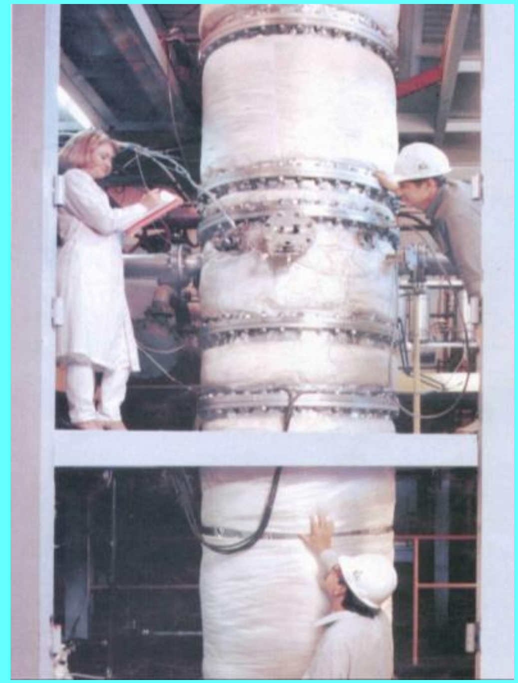
Column for natural gas liquefaction
Air Products and Chemicals (USA)

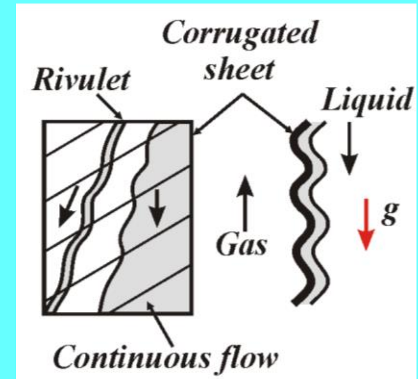




Alekseenko, Markovich, Shtork: ***Phys. Fluids, 1996***

Two-phase flow in distillation column with regular packing





Freon model of distillation column with regular packing (ITP SB RAS)

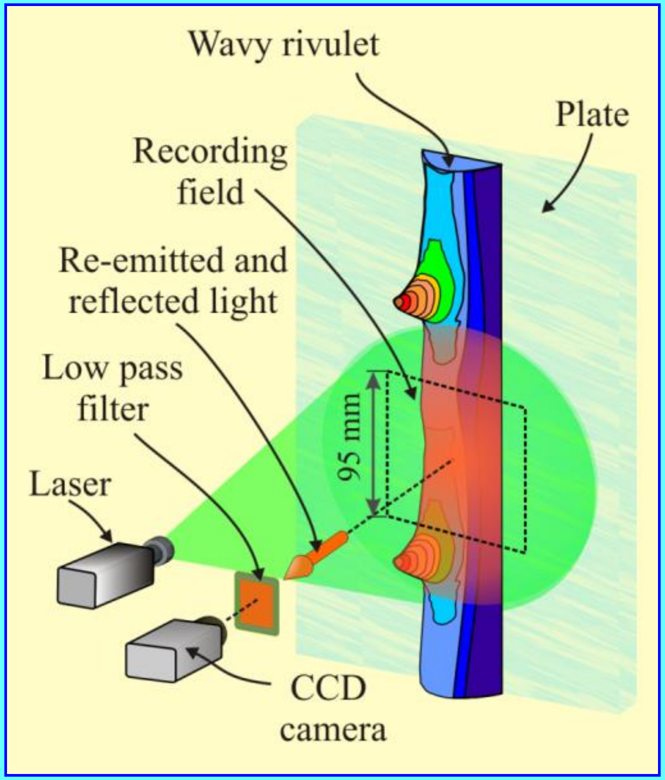
Alekseenko, Markovich, Evseev, Bobylev et al: ***AIChE J., 2008***

Wavy rivulet flow on vertical plate: experiment

Experimental setup and measurement technique

Vertical glass plate or plate with fluoroplastic coating. Plate sizes – 0.2×0.65 m.
Rivulet was formed from slot distributor.

Physical properties of the solutions	Contact angle	Kinematic viscosity, ν, m^2/s	Kinematic surface tension σ/ρ, m^3/s^2
25% water-glycerol solution (WGS)	6 ± 0.2°	$2.4 \cdot 10^{-6}$	$53.9 \cdot 10^{-6}$
45% water-ethanol solution (WES)	23 ± 1°	$2.65 \cdot 10^{-6}$	$32.9 \cdot 10^{-6}$



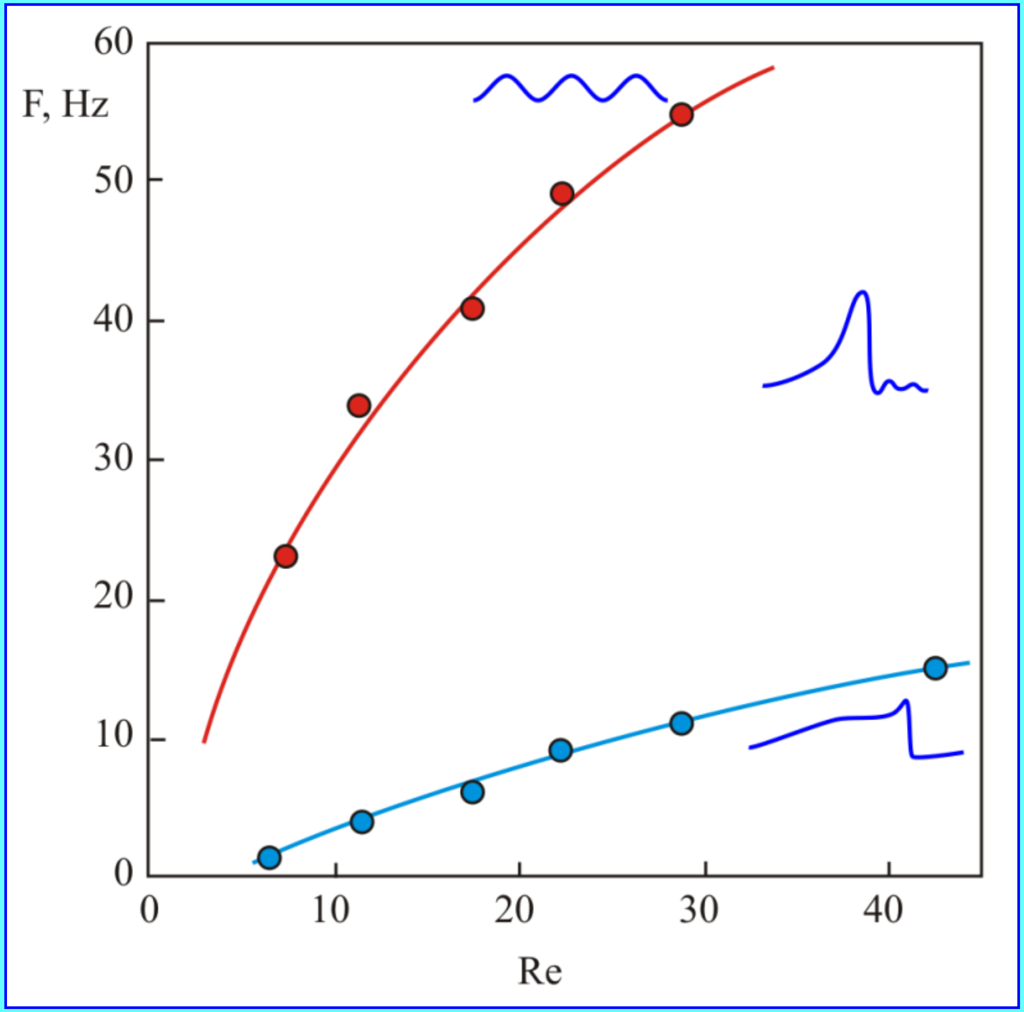
Experimental scheme

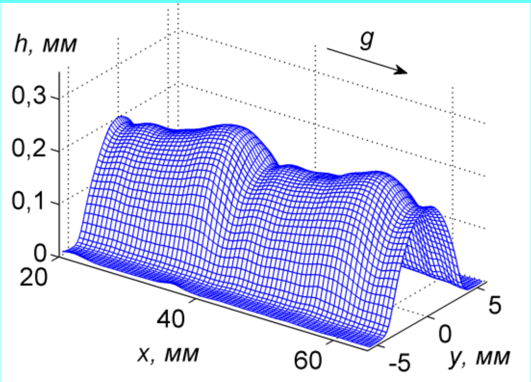
Thickness was measured by the Laser-Induced Fluorescence (LIF) method.

Alekseenko et al.:
Thermophysics & Aeromech., 2010

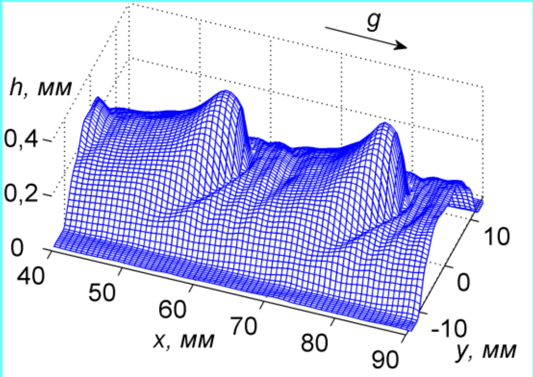
Wavy rivulet flow on vertical plate: experiment

Regions of existence and wave regimes, α = 6°

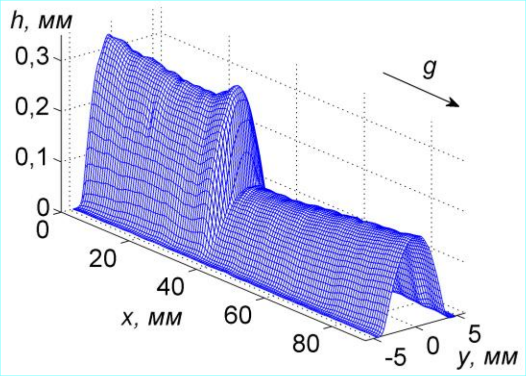




***F* = 15 Hz**
***Re* = 10**



***F* = 23 Hz**
***Re* = 36**



***F* = 1 Hz**
***Re* = 10**

Rivulet width is insensitive to the phase of passing wave

Wavy rivulet flow on vertical plate: theory

Thin rivulet: $h \ll b$; long waves: $h \ll \lambda$ ⟶ **Kapitsa-Shkadov integral model.**

Equations of 3D wavy flow of a thin liquid layer (Demekhin & Shkadov 1984):

$$\frac{\partial q}{\partial t}+\frac{6}{5}\left(\frac{\partial}{\partial x}\frac{q^2}{h}+\frac{\partial}{\partial z}\frac{qm}{h}\right)=\frac{3}{Re_m}\left(h-\frac{q}{h^2}\right)+hWe\frac{\partial \Delta h}{\partial x}, \qquad (1)$$

$$\frac{\partial m}{\partial t}+\frac{6}{5}\left(\frac{\partial}{\partial z}\frac{m^2}{h}+\frac{\partial}{\partial x}\frac{qm}{h}\right)=hWe\frac{\partial \Delta h}{\partial z}-\frac{3m}{Re_m h^2}, \qquad (2)$$

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}+\frac{\partial m}{\partial z}=0. \qquad (3)$$

Here $q=\int_0^h u\,dy,\; m(x,z,t)=\int_0^h w\,dy$ **are flow rates along *Ox* and *Oz* axis, respectively,**

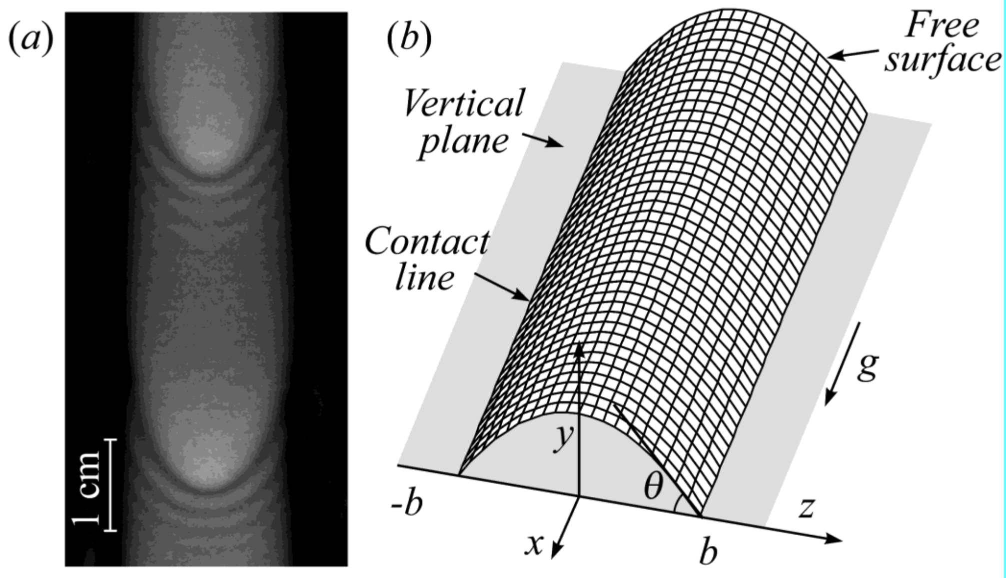
h **is layer thickness,** $\Delta h=\partial^2 h/\partial x^2+\partial^2 h/\partial z^2$ **is surface curvature,**

$Re_m=gh_0^3/3\nu^2$ **is Reynolds number,** $We=\left(3Fi/Re_m^5\right)^{1/3}$ **is Weber number,**

$Fi=\sigma^3/\rho^3 g\nu^4$ **is Kapitsa number,** σ **is surface tension,** ρ **is density,** ν **is kinematic viscosity.**

Wavy rivulet flow on vertical plate: theory

Boundary conditions for rivulet



We use the boundary conditions of constant contact line (or constant rivulet width), determined in authors' experiments, as well as standard conditions of liquid non-slipping on a solid wall, and symmetry conditions:

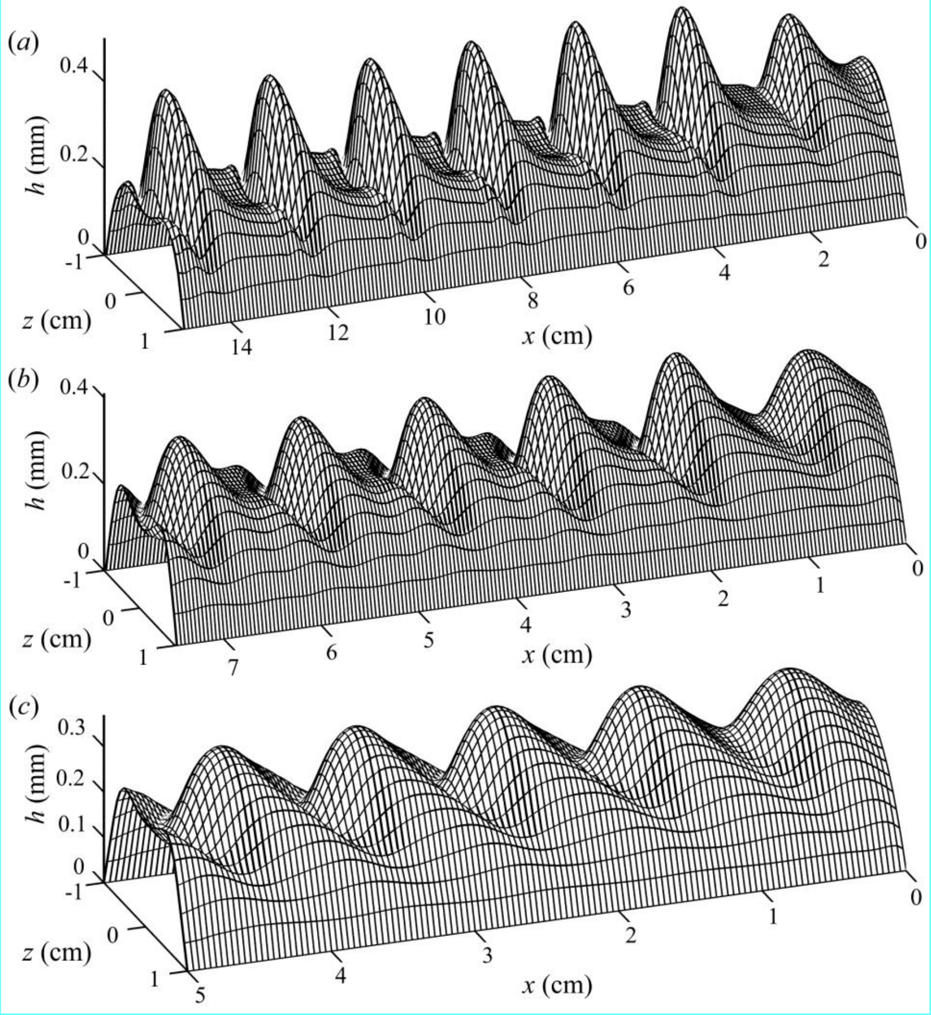
$$h(x,b,t) = q(x,b,t) = m(x,b,t) = 0, \quad m\big|_{z=0} = 0, \quad \partial h/\partial z\big|_{z=0} = \partial q/\partial z\big|_{z=0} = 0$$

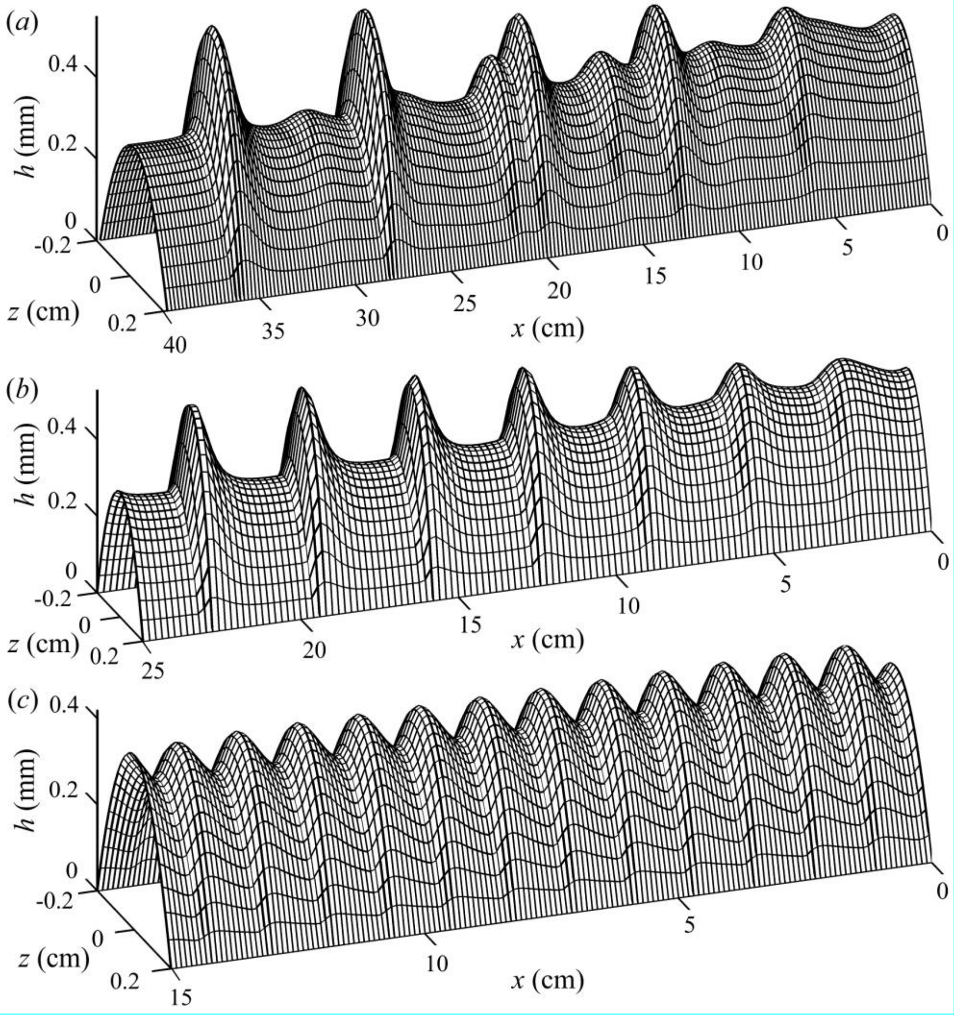
Numerical simulation of waves in rivulet

Alekseenko, Aktershev, Bobylev, Kharlamov, Markovich:
J. Fluid Mech., 2015

Wavy rivulet flow on vertical plate: theory

Evolution of 3D nonlinear waves at Re_m = 25 for different forcing frequencies



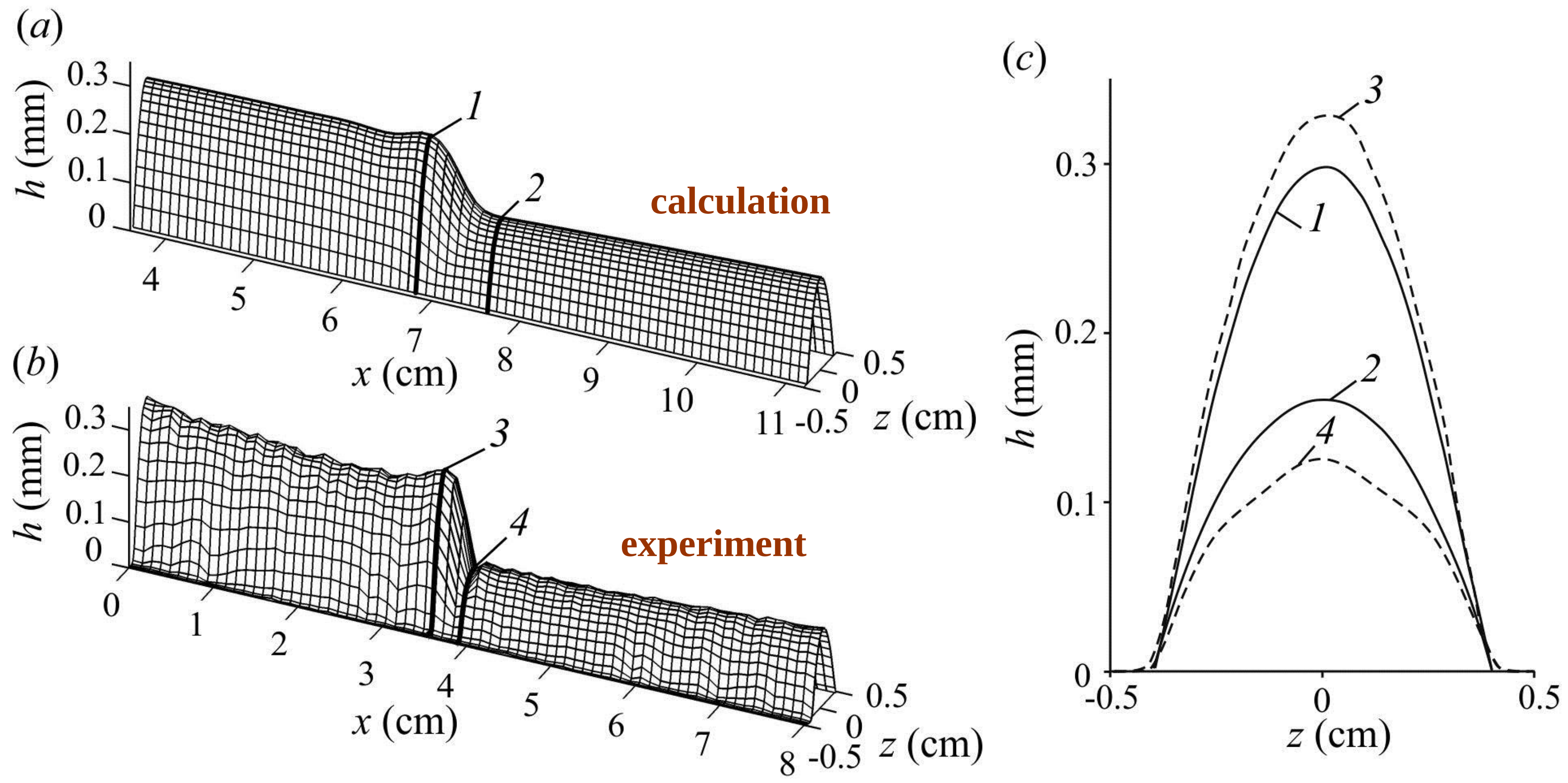


WGS: (*a*) 15 Hz, (*b*) 23Hz, (*c*) 30 Hz

WES: (*a*) 5 Hz, (*b*) 10 Hz, (*c*) 25 Hz

Wavy rivulet flow on vertical plate: theory

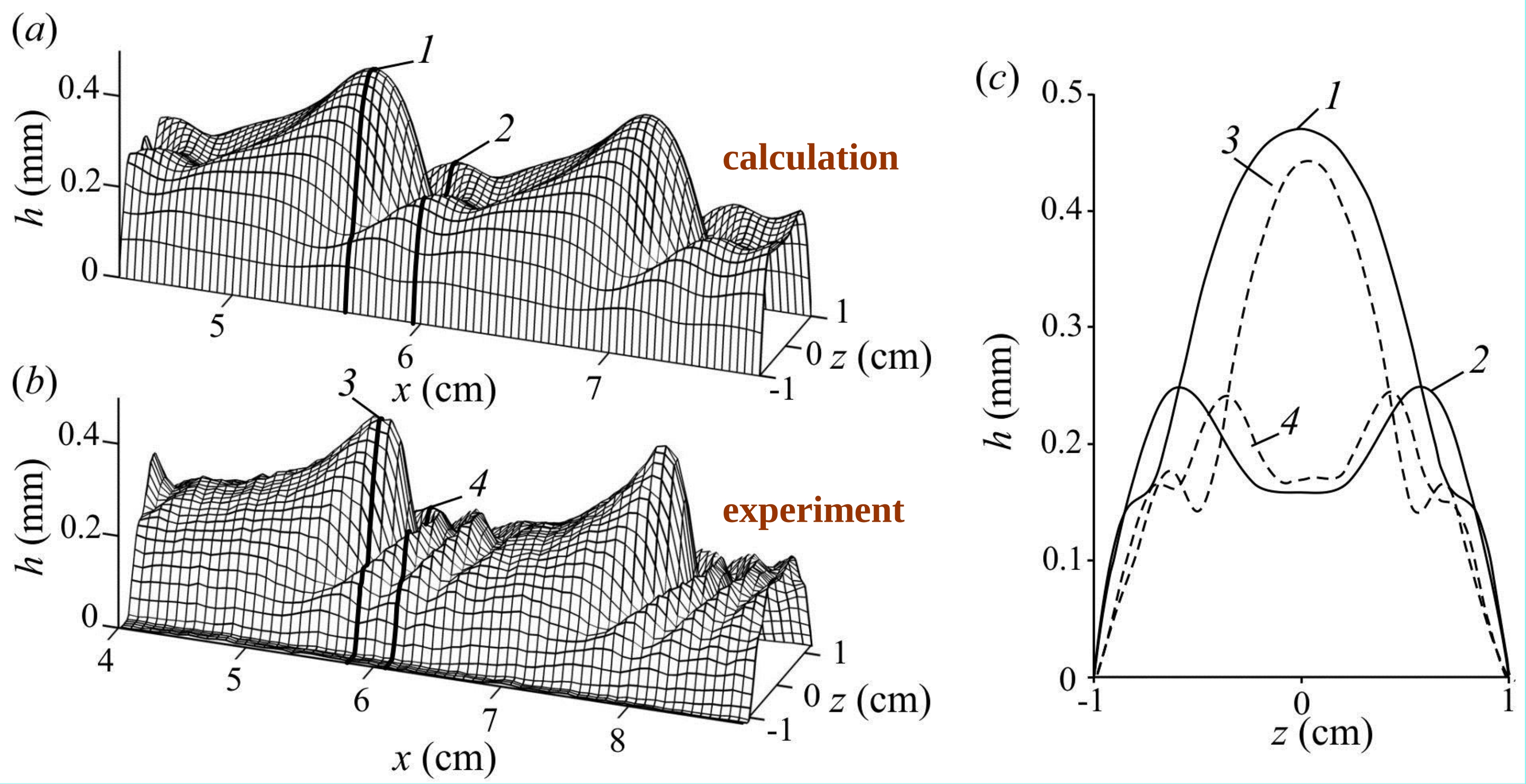
Developed nonlinear waves: comparison with experiment



Shape of low-frequency wave in WGS rivulet compared to the experimental data (Alekseenko *et al*. 2010) at Re_m = 10, f = 1 Hz.
(*a*) calculated 3D surface, (*b*) experimental 3D surface,
(*c*) cross-sections: (1, 2) calculation, (3, 4) experiment.

Wavy rivulet flow on vertical plate: theory

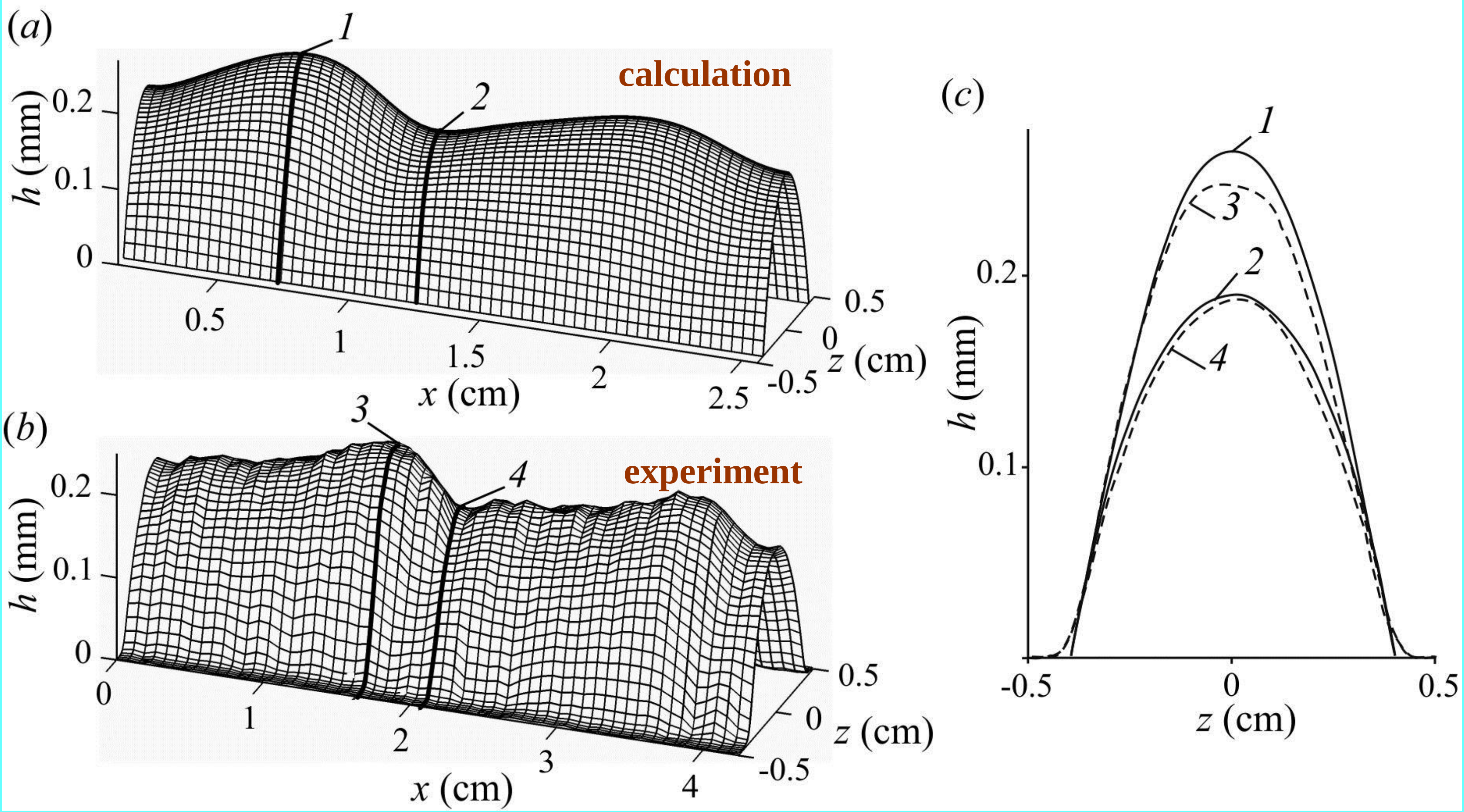
Developed nonlinear waves: comparison with experiment



Shape of developed wave in WGS rivulet compared to the experimental data (Alekseenko *et al*. 2010) at Re_m = 36, *f* = 23 Hz.
(*a*) calculated 3D surface, (*b*) experimental 3D surface,
(*c*) cross-sections: (1, 2) calculation, (3, 4) experiment.

Wavy rivulet flow on vertical plate: theory

Developed nonlinear waves: comparison with experiment



Shape of developed wave in WGS rivulet compared to the experimental data (Alekseenko *et al*. 2010) at Re_m = 10, *f* = 15 Hz.
(*a*) calculated 3D surface, (*b*) experimental 3D surface,
(*c*) cross-sections: (1, 2) calculation, (3, 4) experiment.

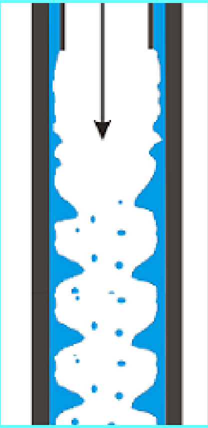
Conclusion

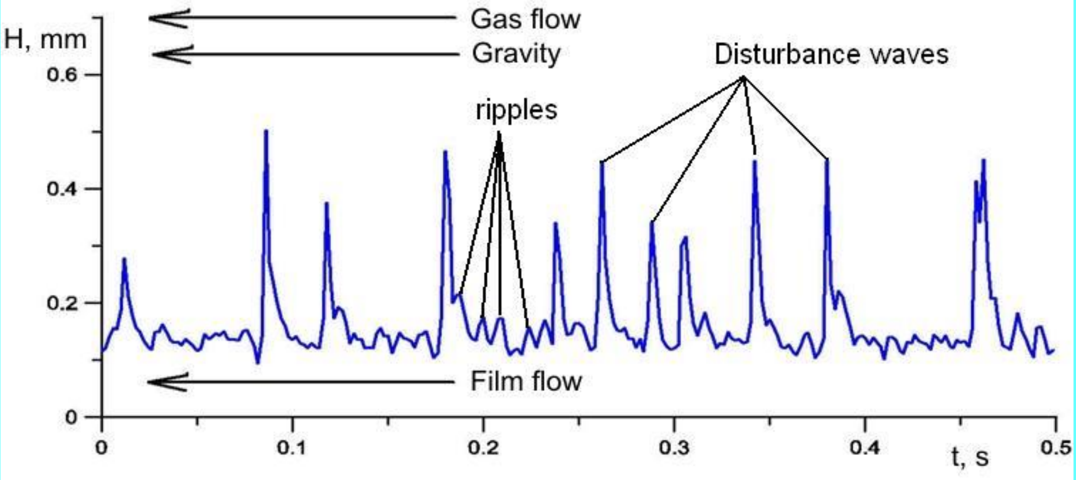
3D regular linear and nonlinear waves in rectilinear rivulet flow along a vertical plate are first described on the basis of numerical simulation. The boundary condition of fixed contact line is accepted in theoretical model using experimental observations. It was demonstrated a good agreement between theory and experiment by 3D shape of rivulet waves.

3. INSTABILITIES IN ANNULAR TWO-PHASE FLOW

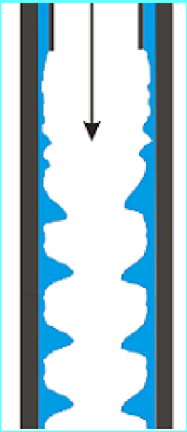
Wave structure of annular gas-liquid flow

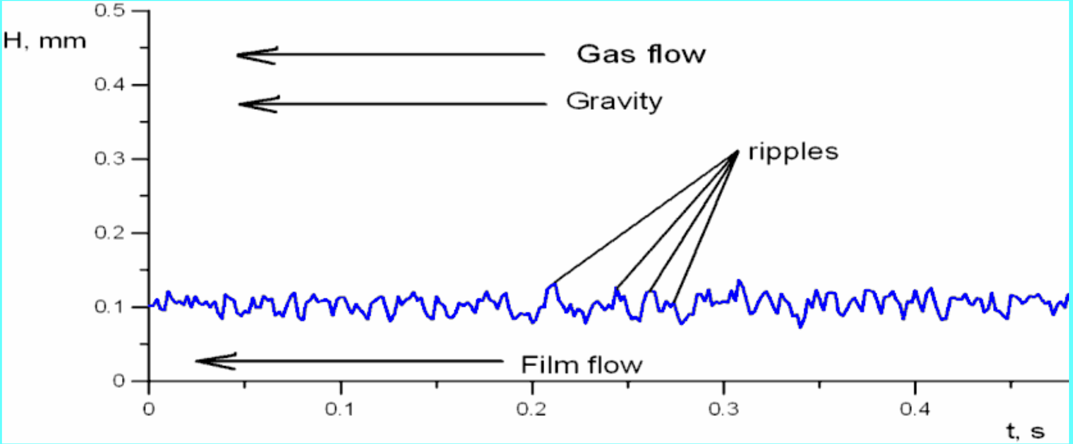
Traditional description of wavy structure in annular flow





Flow with entrainment
$Re_L = 142$,
$V_g = 42$ m/s



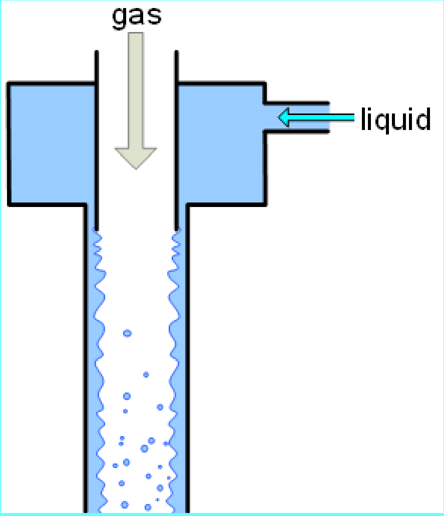


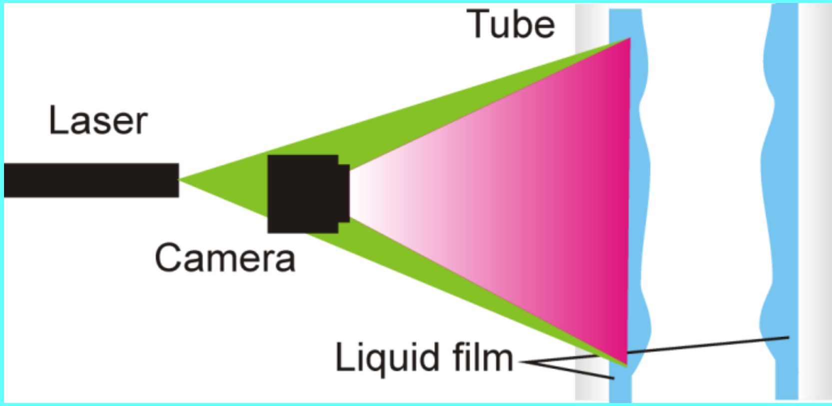
Flow without entrainment
$Re_L = 40$,
$V_g = 42$ m/s

1. Ripples are omnipresent at liquid film surface under intensive gas shear.
2. Transition to entrainment occurs due to inception of disturbance waves.

Wave structure of annular gas-liquid flow

High-speed modification of LIF technique: 2D-approach





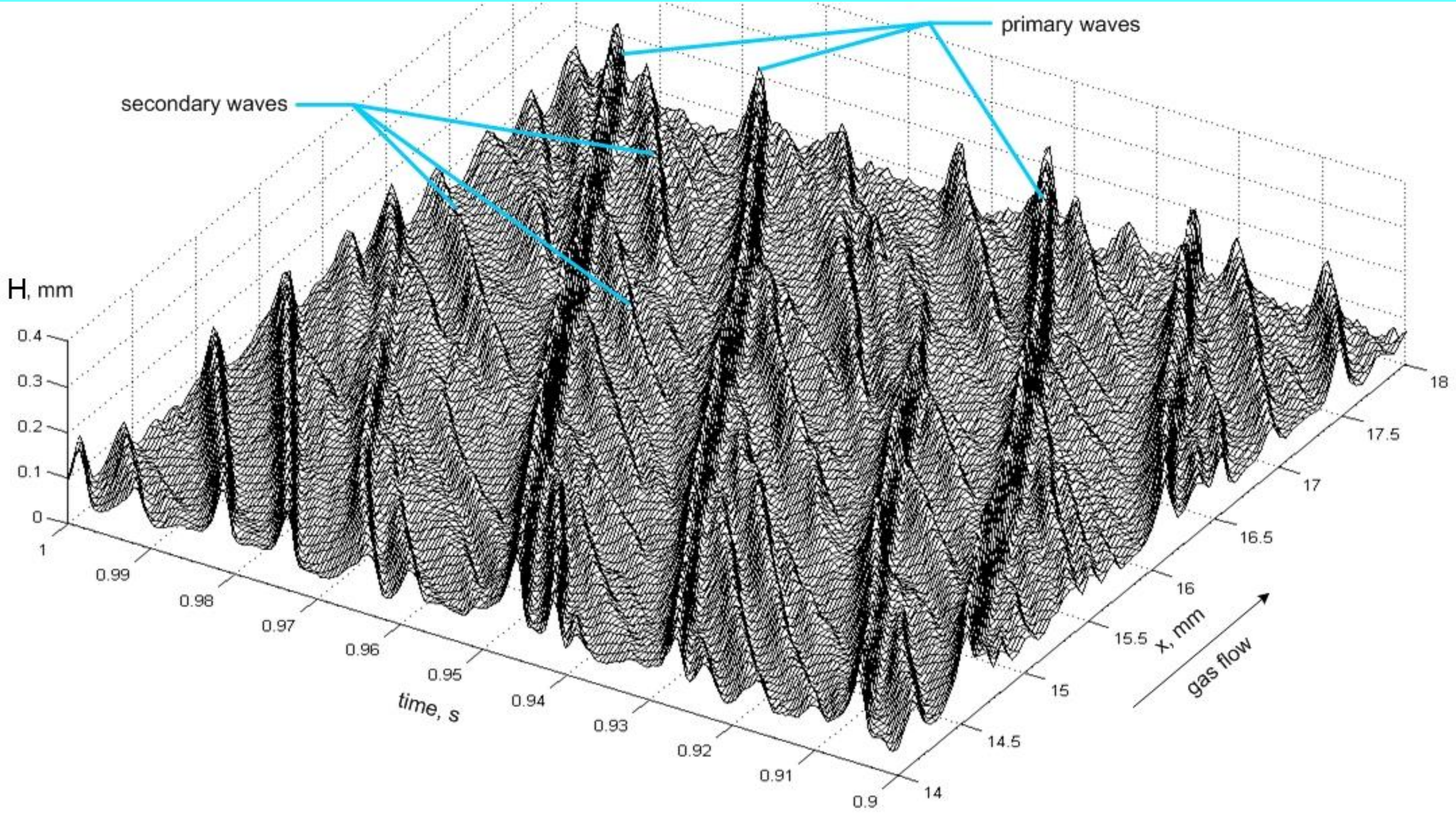
Flow parameters:
Tube's inner diameter d = 15 mm;
Liquid Reynolds numbers $Re_L = q/\pi d\nu$:
Re_L = 16 - 520;
Average gas velocities V_g = 18 - 80 m/s;
Distance from the inlet 5 - 60 cm;
Working liquids – water and water-glycerol solutions with ν = 1.5, 1.9, 3*10^{-6} m^2/s.

Light source: Continuous green laser, wavelength 532 nm, power 2 W
Fluorescent matter – Rhodamine 6G, in concentration 30 mg/l
Resolution (depends on task):
Camera sampling rate: 2 - 50 kHz;
Exposure time: 2 – 100 µs;
Spatial resolution: 0.1 mm;
Accuracy: 2 – 3%

Alekseenko, Antipin, Cherdantsev, Kharlamov, Markovich:
Microgravity Science and Technology, 2008

Wave structure of annular gas-liquid flow

No-entrainment regimes. Primary and secondary waves

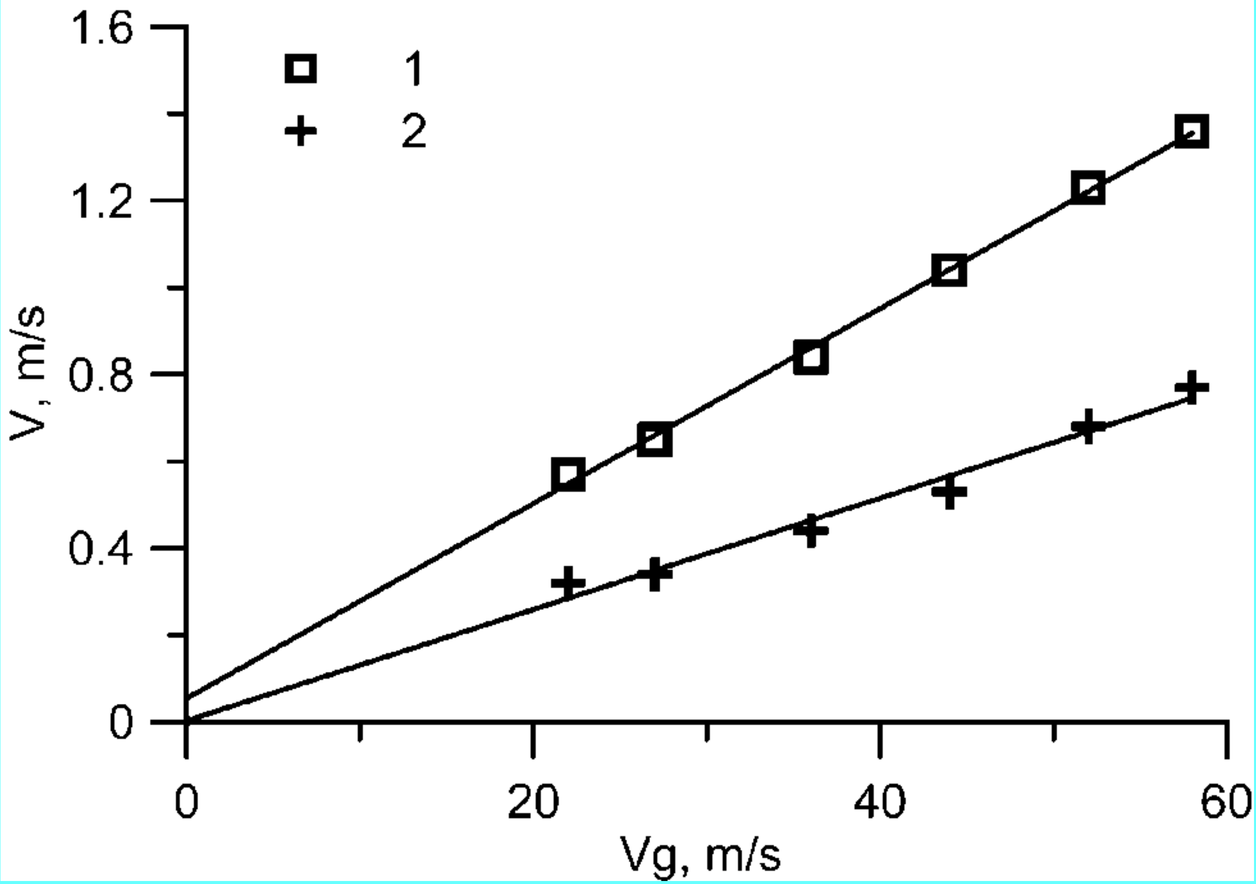


Primary and secondary waves in regimes without entrainment.
All secondary waves are generated at the back slopes of primary waves.

$Re_L = 40$, $V_g = 27$ m/s.

Wave structure of annular gas-liquid flow

No-entrainment regimes. $Re_L = 40$.



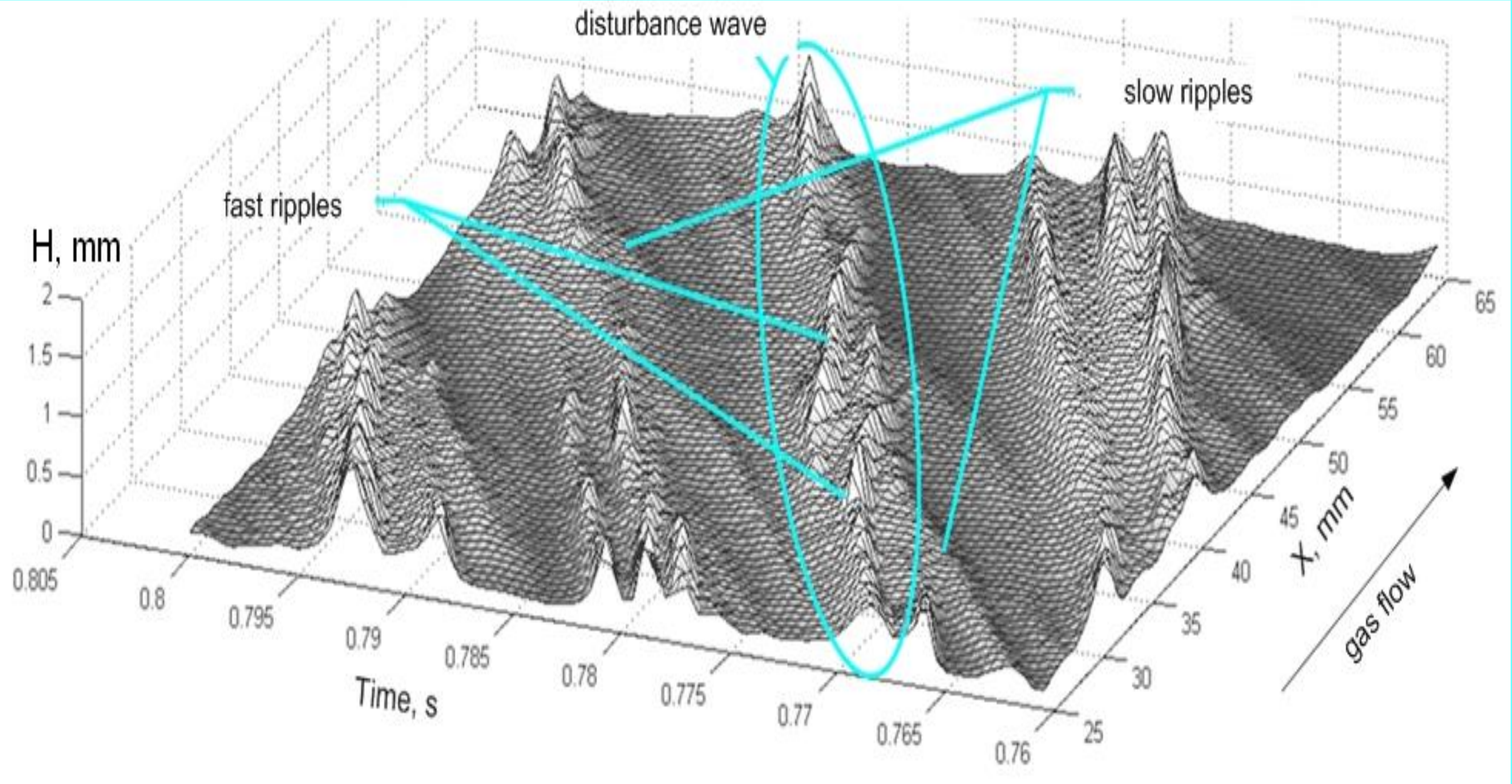
1 - primary waves

2 - secondary waves

Alekseenko, Cherdantsev, Cherdantsev, Markovich:
Microgravity Science and Technology, 2009

Wave structure of annular gas-liquid flow

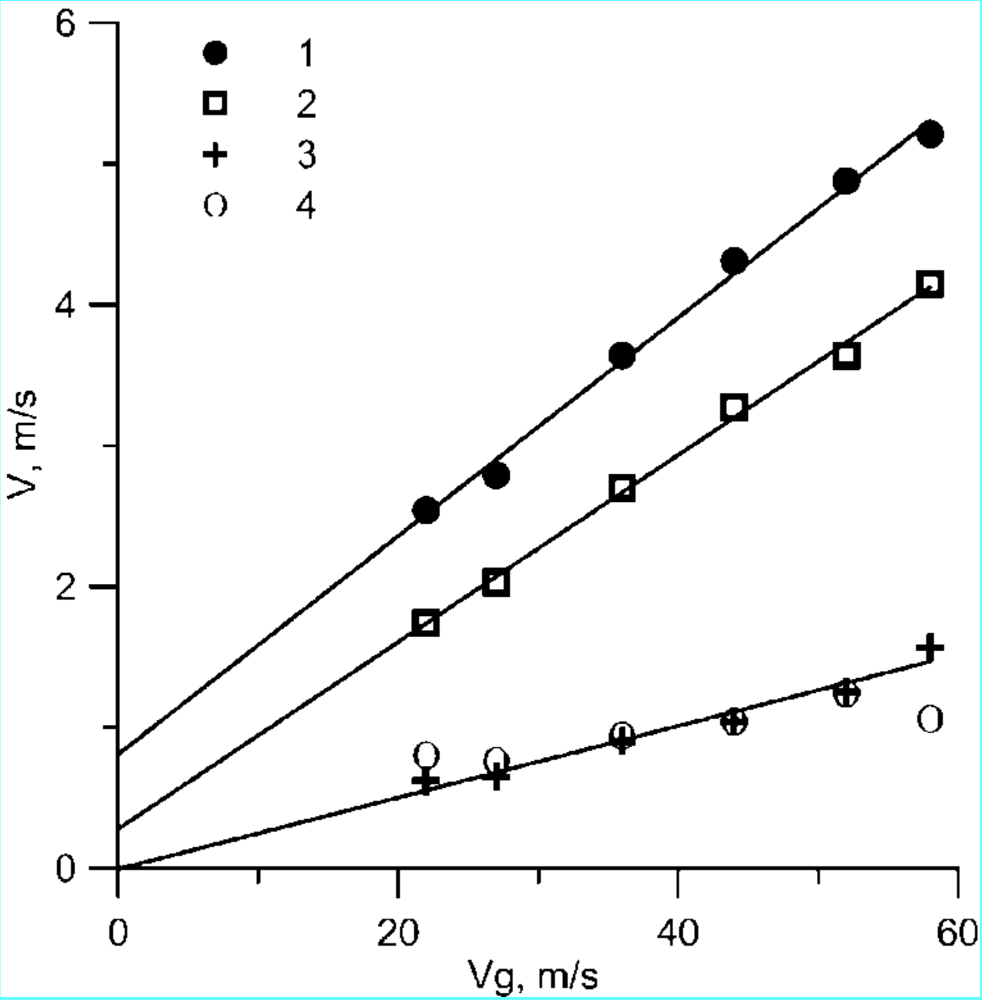
Entrainment regimes. Disturbance waves and two types of ripples: fast and slow ripples



Fast ripples on the disturbance wave and slow ripples on the residual layer. $Re_L = 350$, $V_g = 27$ m/s.

Wave structure of annular gas-liquid flow

Entrainment regimes. $Re_L = 350$



1 - fast ripples

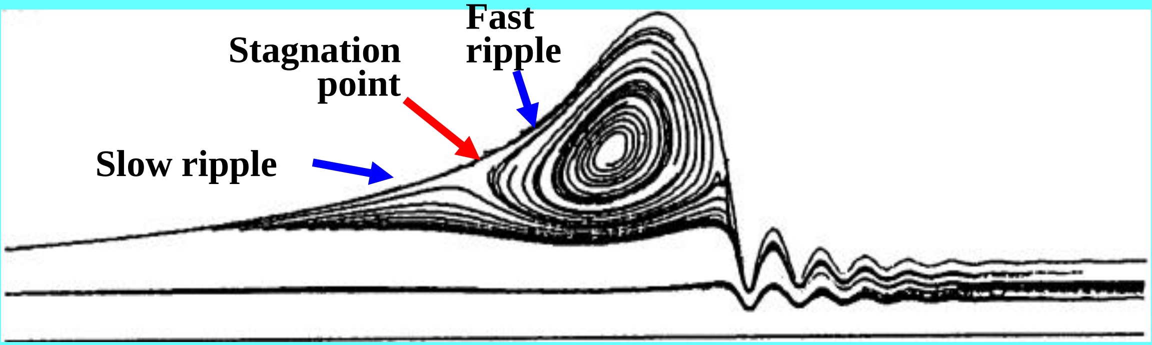
2 - disturbance waves

3 - slow ripples

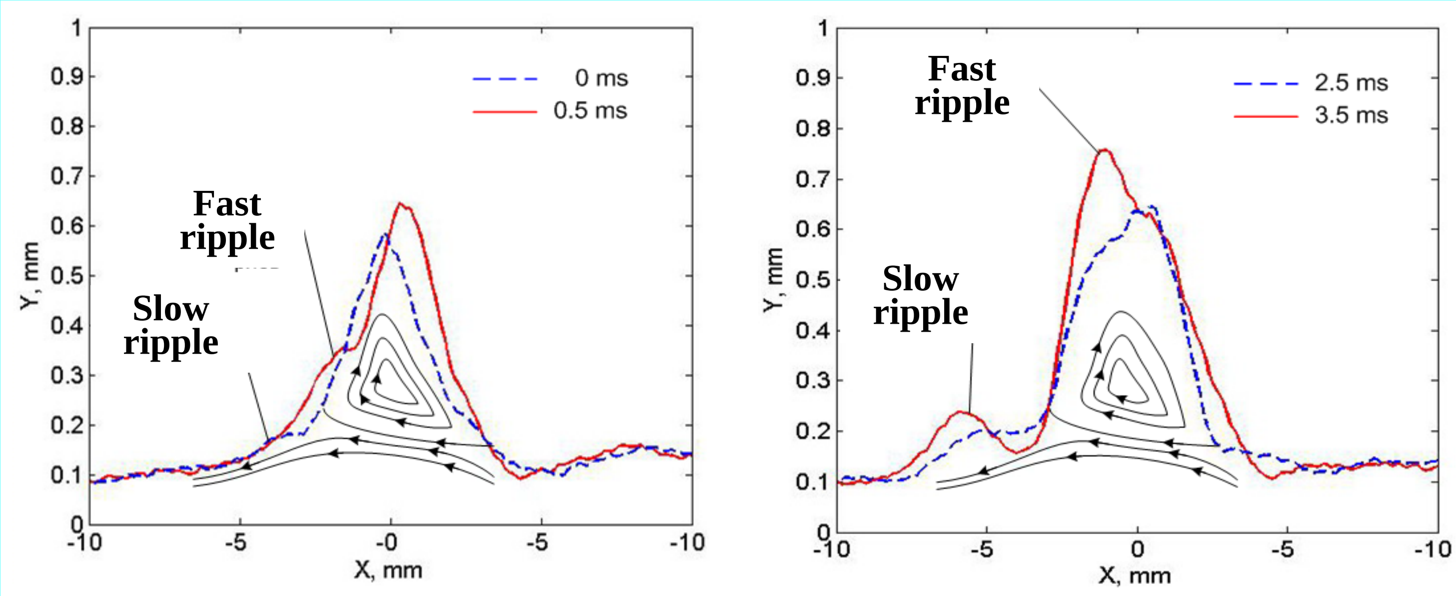
Alekseenko, Cherdantsev, Cherdantsev, Markovich:
Microgravity Science and Technology, 2009

Wave structure of annular gas-liquid flow

Possible explanation of the formation of fast and slow ripples



Stream lines in the reference system of the wave (Miyara, 1999)

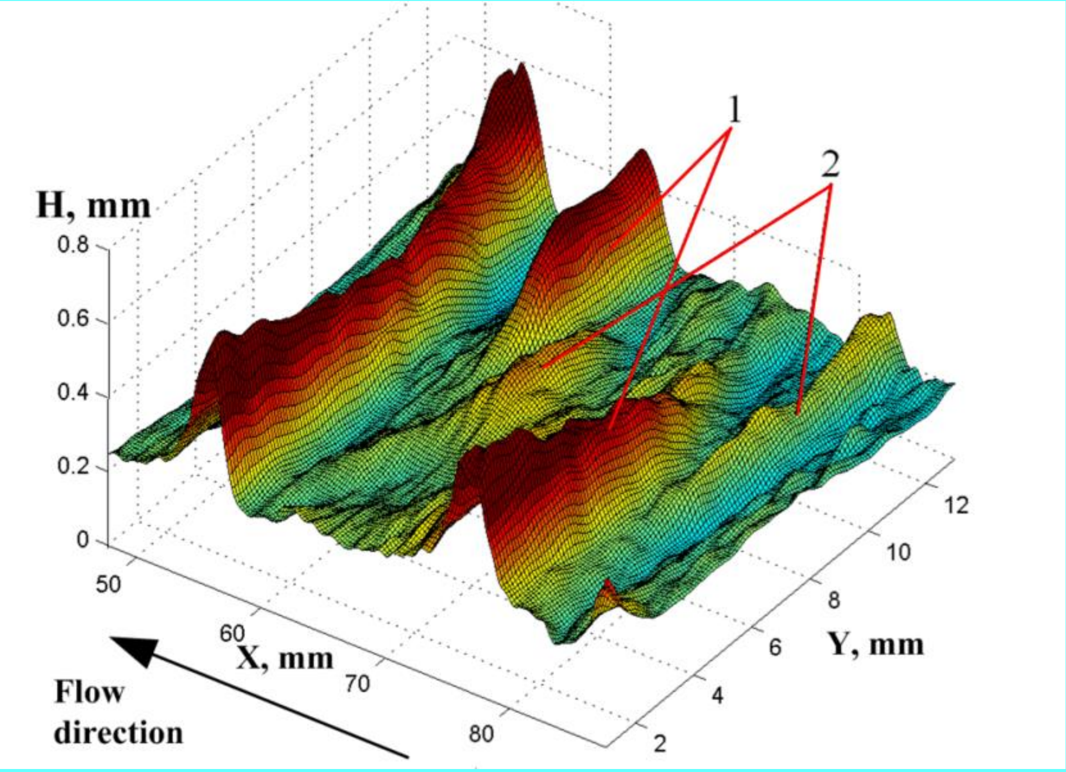


Evolution of the wave profile

Alekseenko, Antipin, Cherdantsev, Kharlamov, Markovich: ***Physics of Fluids, 2009***

Wave structure of annular gas-liquid flow

High-speed modification of LIF technique - 3D-approach



Appearance of edges of primary waves means that not all the primary waves form full rings around the circumference of the pipe.

The edges of primary waves do also generate secondary waves, as well as central parts of primary waves.

1 – Edges of primary waves. 2 – Secondary waves, generated at the edges of primary waves.
Re_L = 18, WGS, V_g =18 m/s.

Alekseenko, Cherdantsev, Cherdantsev, Isaenkov, Kharlamov, Markovich: Exp. Fluids, 2012

Conclusion

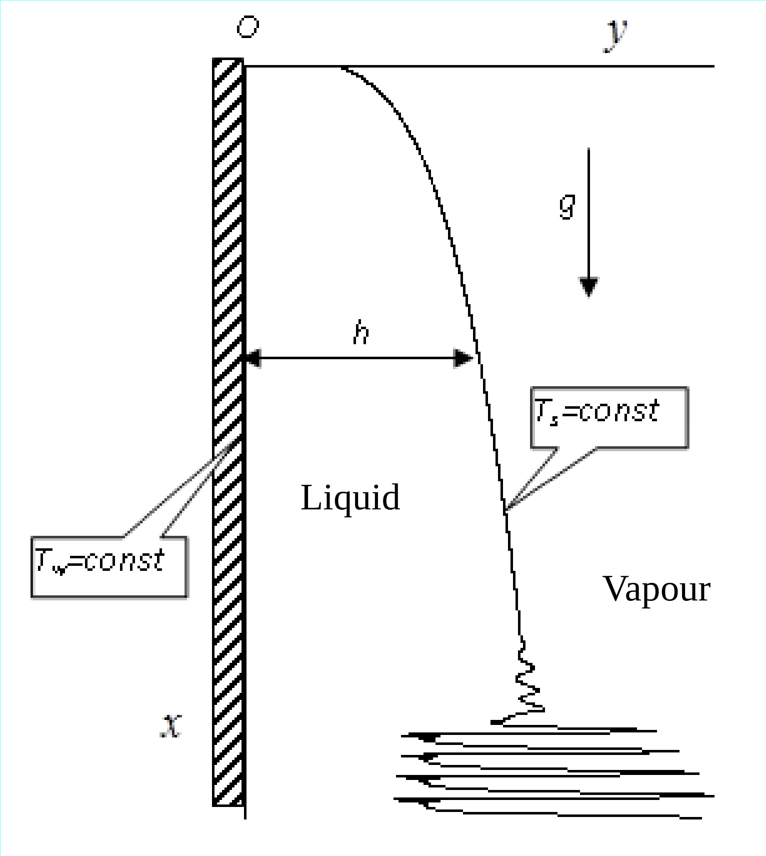
Interfacial waves in annular two-phase flow are studied in detail with using high-speed modification of LIF technique. It was demonstrated the existence of two-wave structure of interphase. In case of flow with droplet entrainment small ripples consist of fast and slow ones. Namely fast ripple is responsible for droplet entrainment from the crests of large disturbance waves. The examples of measuring 3D shape of interface are presented.

4. TRANSPORT PHENOMENA:

Wave effect on condensation

Statement of the problem

Film with condensation



- Wall temperature $T_w = const$; saturated vapor with the temperature $T_s = const$.
- A liquid **film** is a main contributor to the **thermal resistance**.
- The contribution of the **reactive force** due to phase transition is neglected.
- Film surface perturbation is considered to be the **long-wave**
- Thermophysical properties are considered **constant.**

Dimensionless equations of non-isothermal film flow

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{6F_0 q^2}{5h}\right)=\frac{3}{\chi Re_m}\left(h-\frac{F_1 q}{h^2}\right)+\chi^2 Weh\frac{\partial^3 h}{\partial x^3},$$

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=\pm\frac{A}{\chi Re_m h},$$

$$\frac{\partial\theta}{\partial t}+u\frac{\partial\theta}{\partial x}+\frac{W}{h}\frac{\partial\theta}{\partial\eta}=\frac{1}{\chi Re_m Pr h^2}\frac{\partial^2\theta}{\partial\eta^2}.$$

Here q is flow rate,
h is film thickness,
θ is liquid temperature,

$$F_0=1-A/(4+A)^2,$$
$$F_1=1+A/(4+A)$$
$$A=\varepsilon\frac{\partial\theta}{\partial\eta}\Big|_{\eta=1}$$

Dimensionless criteria:

$Re_m=gh_m^3/3\nu^2$ – Reynolds number at the inlet

$\varepsilon=c_p\Delta T/(r\cdot Pr)$ – phase transition intensity

$Fi=\sigma^3/\rho^3 g\nu^4$ – Kapitsa number, Pr – Prandtl number

$\chi=h_m/l$ – linear scales ratio

$We=(3Fi/Re_m^5)^{1/3}$ – Weber number

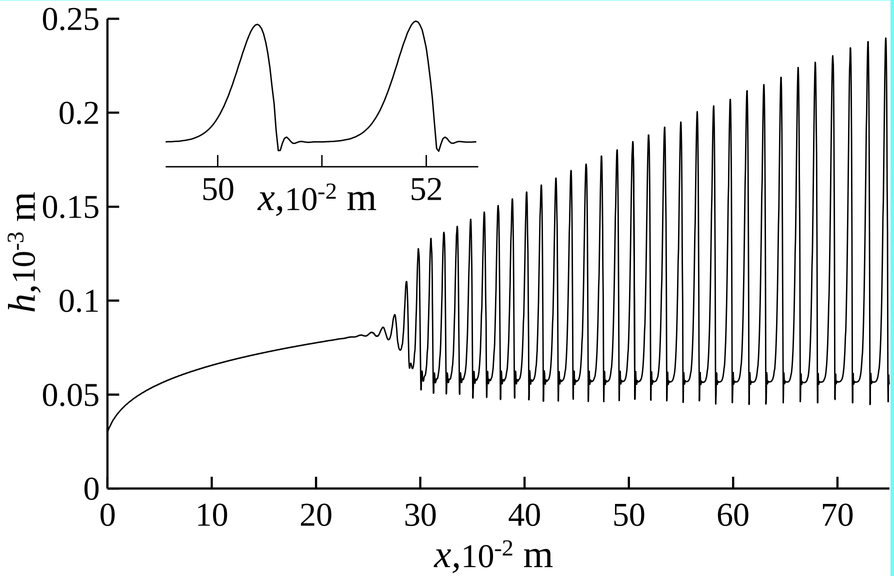
$Nu(x,t)=\frac{1}{(3Re_m)^{1/3}h(x,t)}\frac{\partial\theta}{\partial\eta}\Big|_{\eta=0}$ – Nusselt number

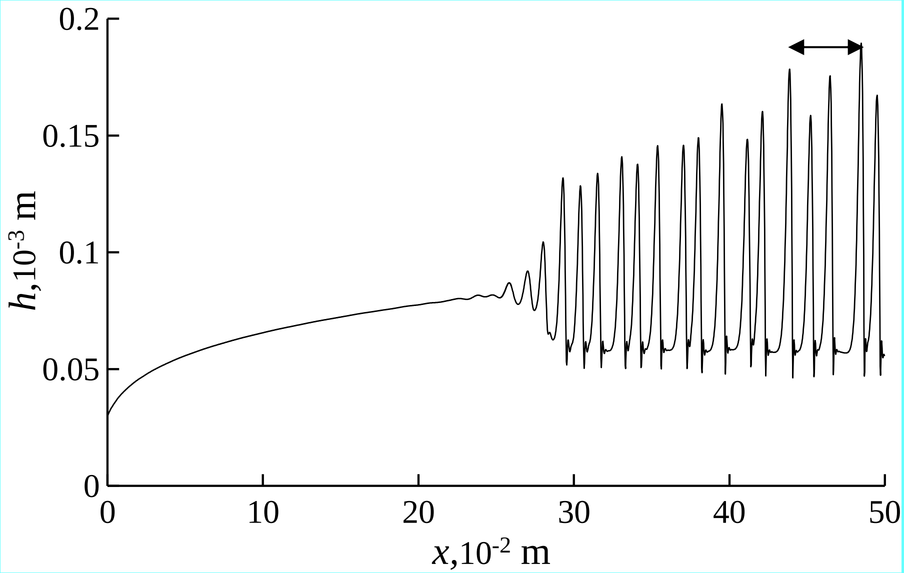
All calculations were carried out for water at t = 373 K (ε = 0.005)

Aktershev, Alekseenko: Phys. Fluids, 2013

Forced waves

Condensation: $Re_m = 1$; $\varepsilon = 0.005$





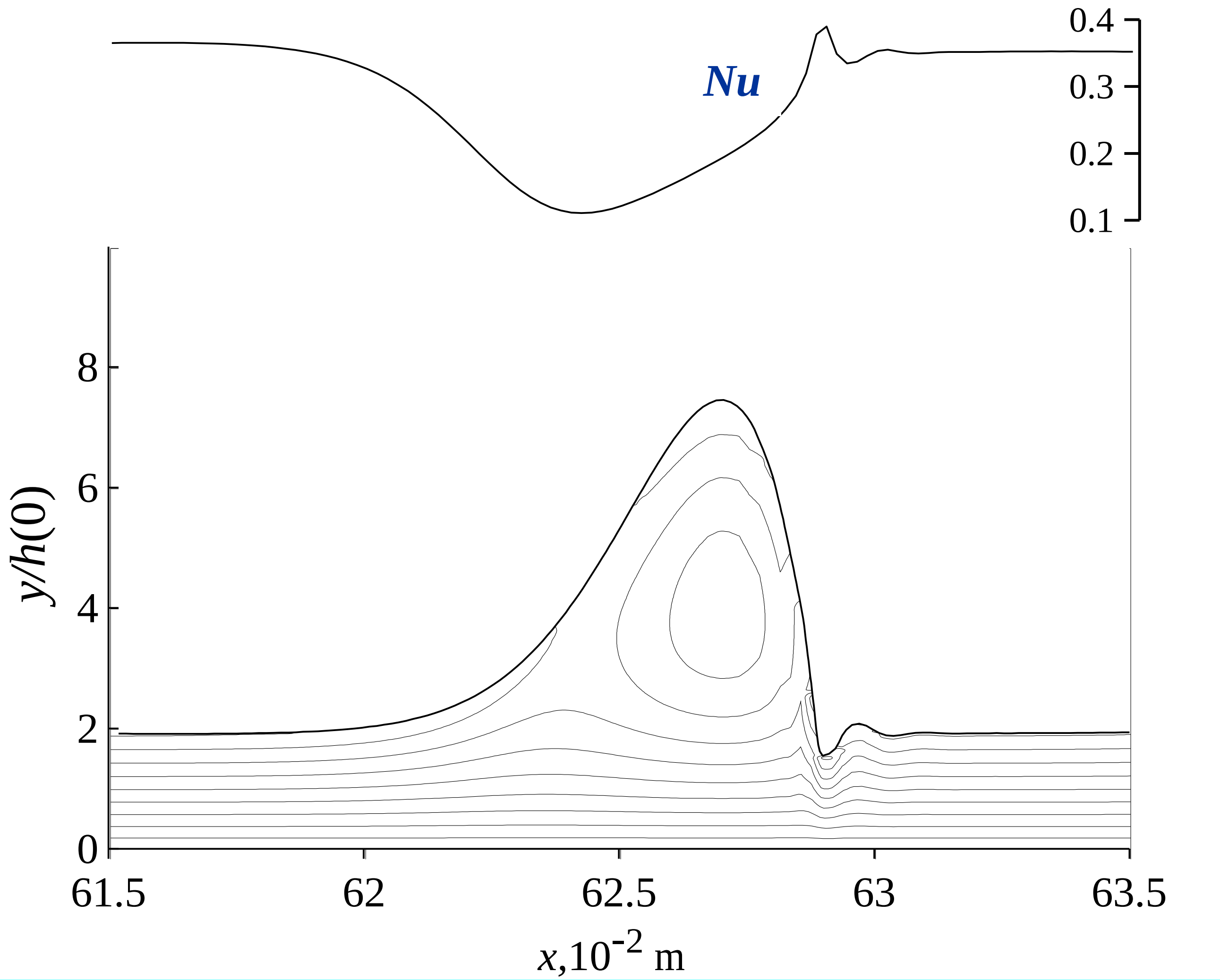
Waves with a frequency 18 Hz. Wave structure is shown in detail in the left upper part.

Amplitude of developed waves increases with distance from the inlet.

Waves with a frequency of 6 Hz. Double-arrow section corresponds to «wave length».

Intermediate peaks appear at low frequencies.

Wave effect on condensation



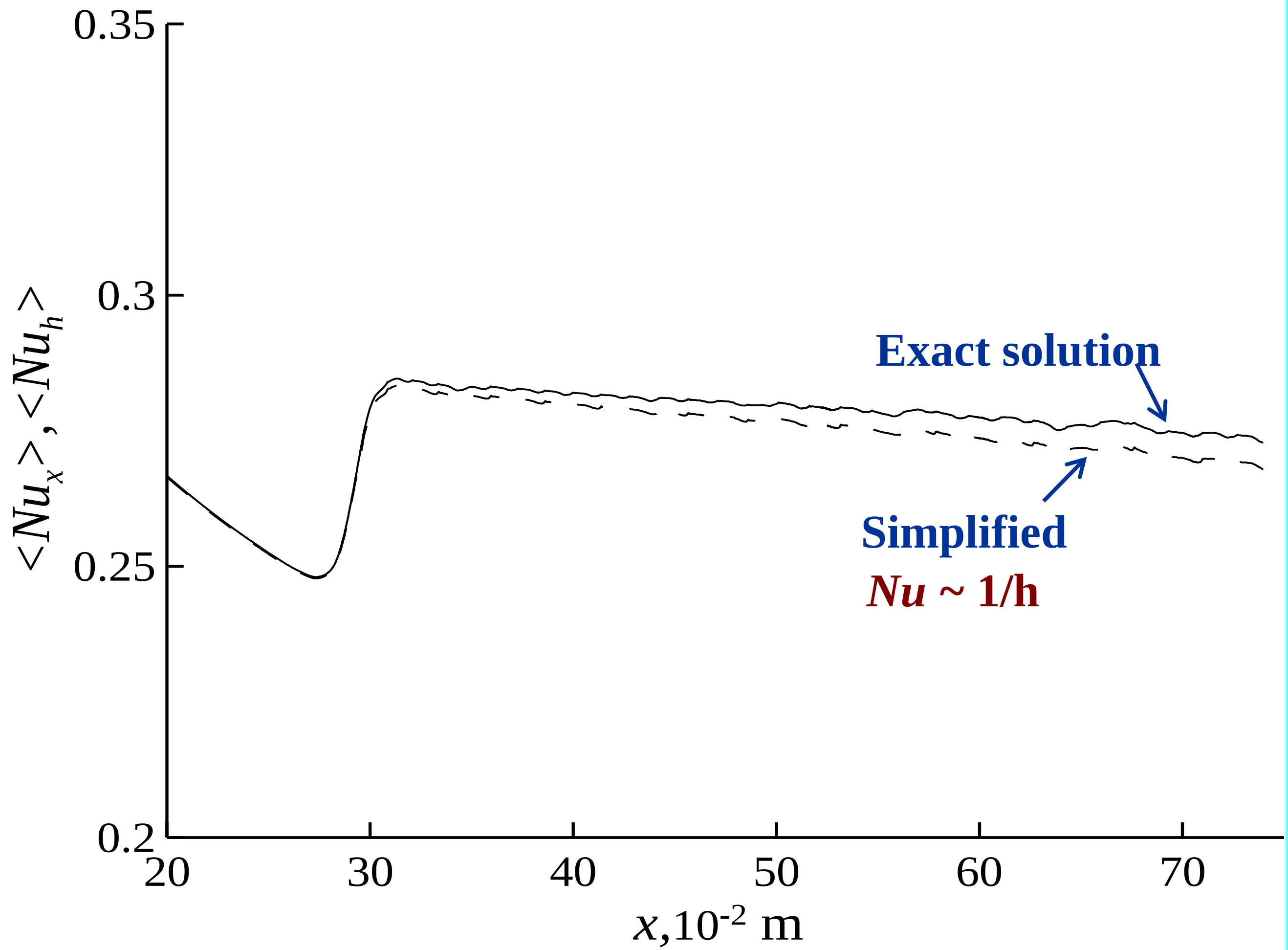
Spatial distribution of Nusselt number along the wave

The streamlines in a reference frame moving with the wave.

Wave velocity 0.27 m/s. Recirculation zone is observed near the wave crest.

The main contribution to the heat transfer enhancement due to waves is caused by area between the peaks, because film thickness is minimal there; while the length of this area is substantially greater than the length of the peak.

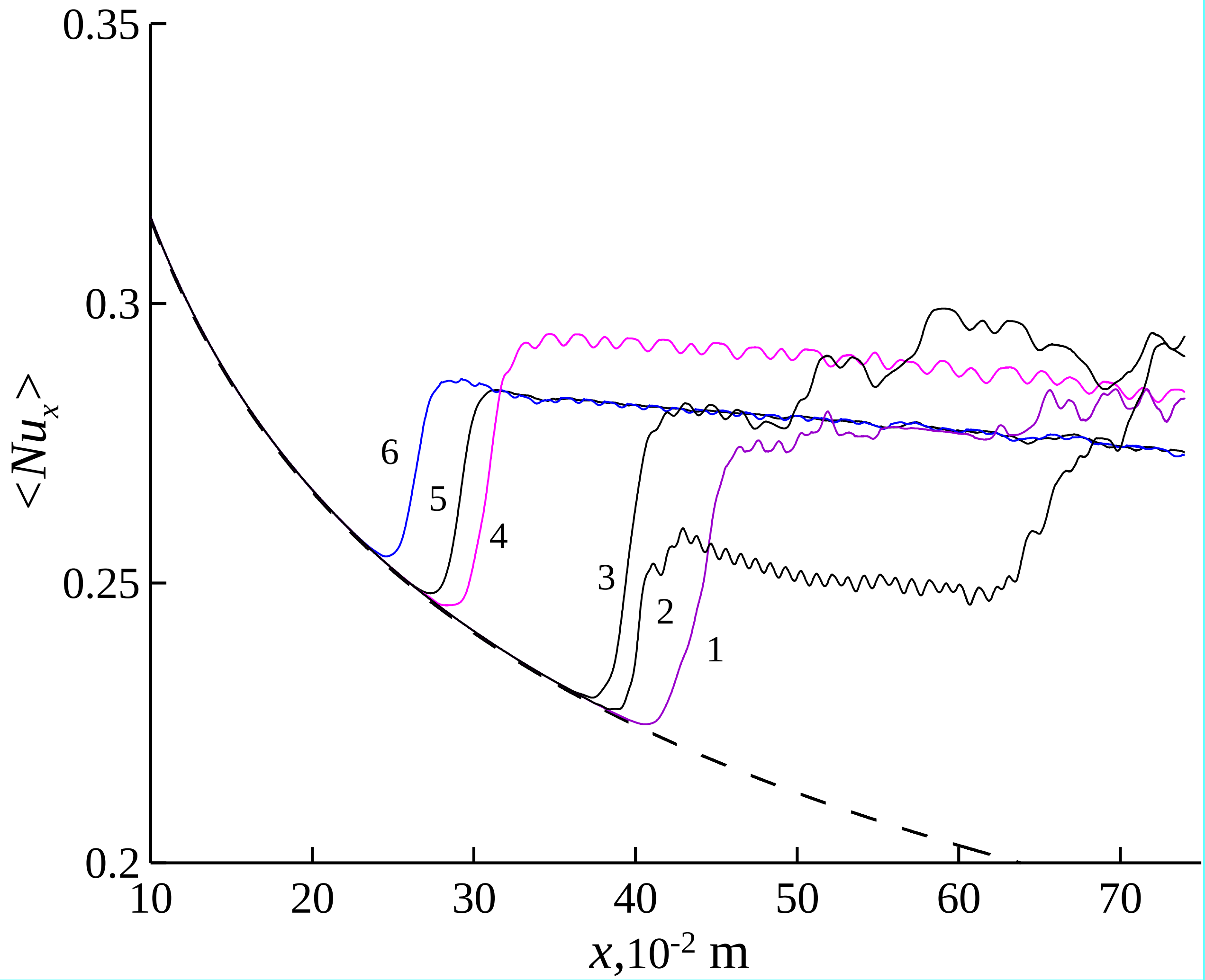
Wave effect on condensation



Dependence of time-averaged Nusselt number on coordinate at f = 18 Hz; solid line is exact solution; dashed line corresponds to calculation by simplified formula:

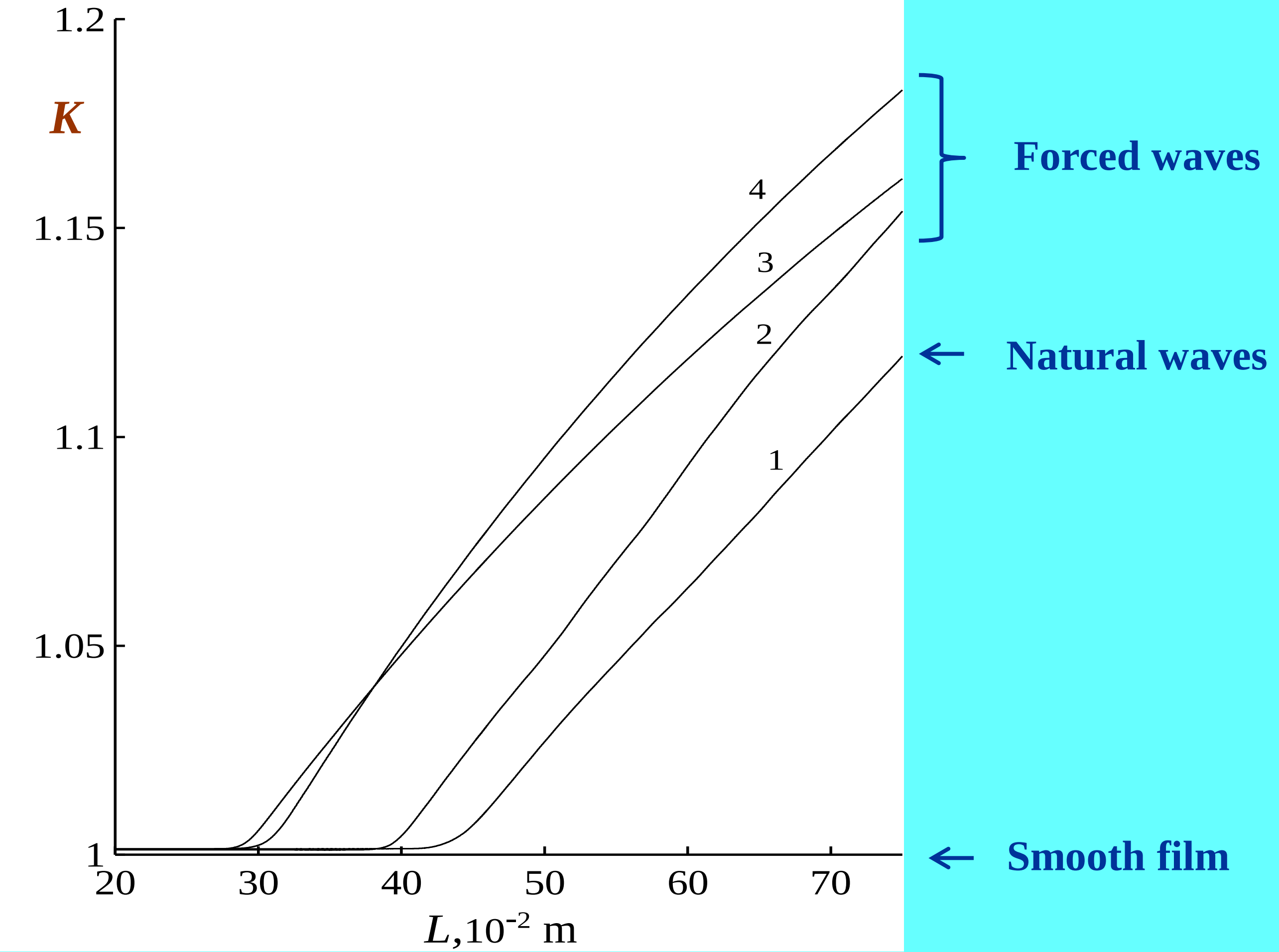
$$\langle Nu_h \rangle = \left(3\mathbf{Re}_m\right)^{-1/3} \langle 1/h \rangle$$

Wave effect on condensation



Dependence of time-averaged Nusselt number on coordinate;
1 – natural waves. Forced waves: 2–25 Hz, 3–3 Hz, 4–5 Hz, 5–18 Hz, and 6–9 Hz;
dashed line shows theoretical value for smooth film.

Wave effect on condensation



Dependence of the dimensionless integral coefficient of heat transfer enhancement *K* on the plate length *L*; 1 – natural waves.
Forced waves: 2 – 3 Hz, 3 –18 Hz, 4 – 5 Hz; *K* = 1 – smooth film.

Conclusion

The wave effect on condensation was studied theoretically. It was shown that heat transfer enhancement by the waves occurs mainly due to a decrease in film thickness between the peaks.

It is demonstrated that using the method of superimposed periodic oscillations, one can enhance heat transfer within a certain frequency range as compared to the case of naturally occurring waves, and especially smooth film.

Instead of general conclusion: Problems and tasks related to film flows

1. Nonlinear three-dimensional waves
2. Stochastization of wavy regimes and transfer to turbulence
3. Interfacial turbulence
4. Interfacial stability in an annular two-phase flow
5. Mechanisms of drop entrainment in an annular two-phase flow
6. Countercurrent flow in regular packing. Maldistribution
7. Flooding and emulsification
8. Formation and stability of dry spots
9. Wave flow of rivulets and bridges
10. Wave effect on transfer processes
11. Condensation of vapor with non-condensable additions
12. Heat transfer in a liquid film will a local heat source
13. Stability and transfer processes in liquid films on rotating and moving bodies
14. Two-phase flow and heat transfer in capillary channels
15. Augmentation of transfer processes in film apparatuses
16. Nanofilms and nanofluids