SURFACE HEAT TRANSFER EXPERIMENTS IN FliHy

Fusion Sciences and Technology Group

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SURFACE HEAT TRANSFER EXPERIMENTS (present status)

The experiment features:

- Liquid layer (water) flows down an inclined chute of 4-m long and 40-cm wide.
- The liquid is heated from the free surface using IR heater.
- Surface temperature behind the heater is measured and recorded by IR camera.
- The flow thickness is measured with ultrasound transducer as a function of time.
- Dye technique and high-speed camera are used to visualize the flow at the surface.

FliHy PARAMETERS AND BASIC FLOW DIAGNOSTICS

- Ultrasound transducer
- Infrared camera
- Color dye technique
- PIV system (in the near future)

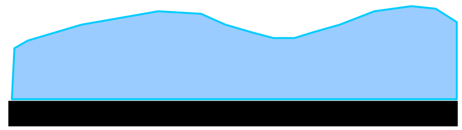
Chute inclination angle:	1-90°
Adjustable nozzle:	3 mm - 5 cm
Heater power:	up to 60 kW
Volumetric flow rate:	5-70 l/s

STUDY OF TURBULENT TRANSPORT IN REGIMES WITH SURFACE RENEWAL

A

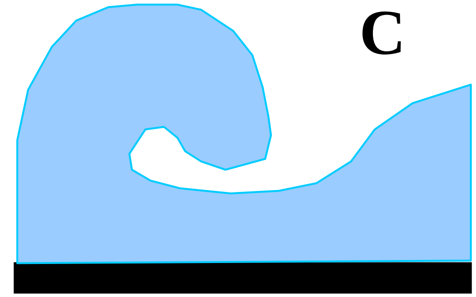
Fr<1
Smooth surface

B



Fr>1
Wavy surface without renewal

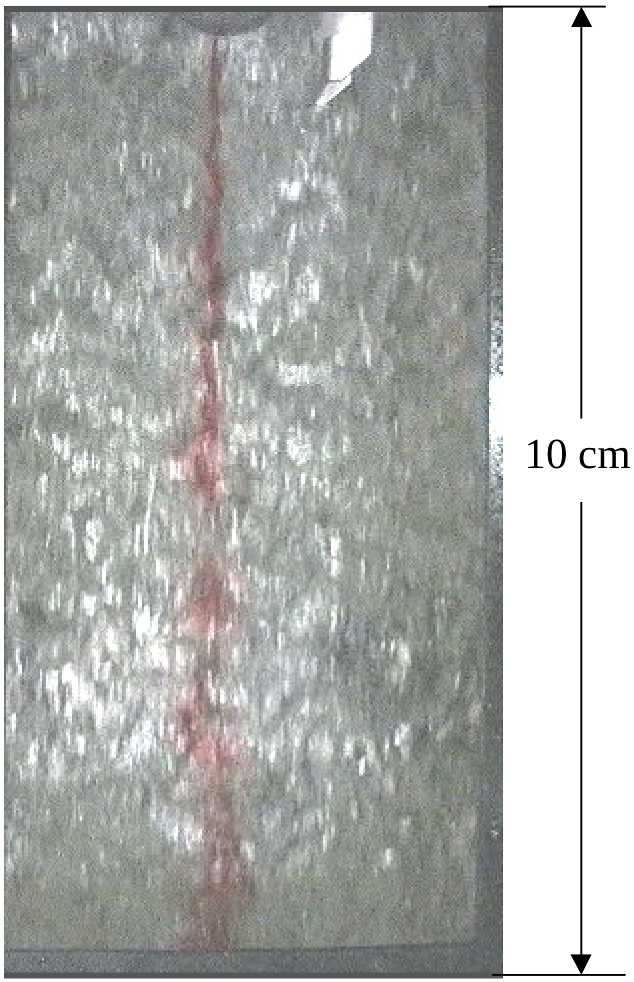
C



Fr>>1
Wavy surface with renewal

- Non-linear surface waves propagating both downstream and upstream
- Overturning waves
- Liquid particles at the surface penetrate into the flow bulk
- Turbulence production near the wall and near the surface
- Bulk-surface / surface-bulk interaction
- Significant intensification of turbulent transport

SURFACE DIAGNOSTICS USING RED DYE

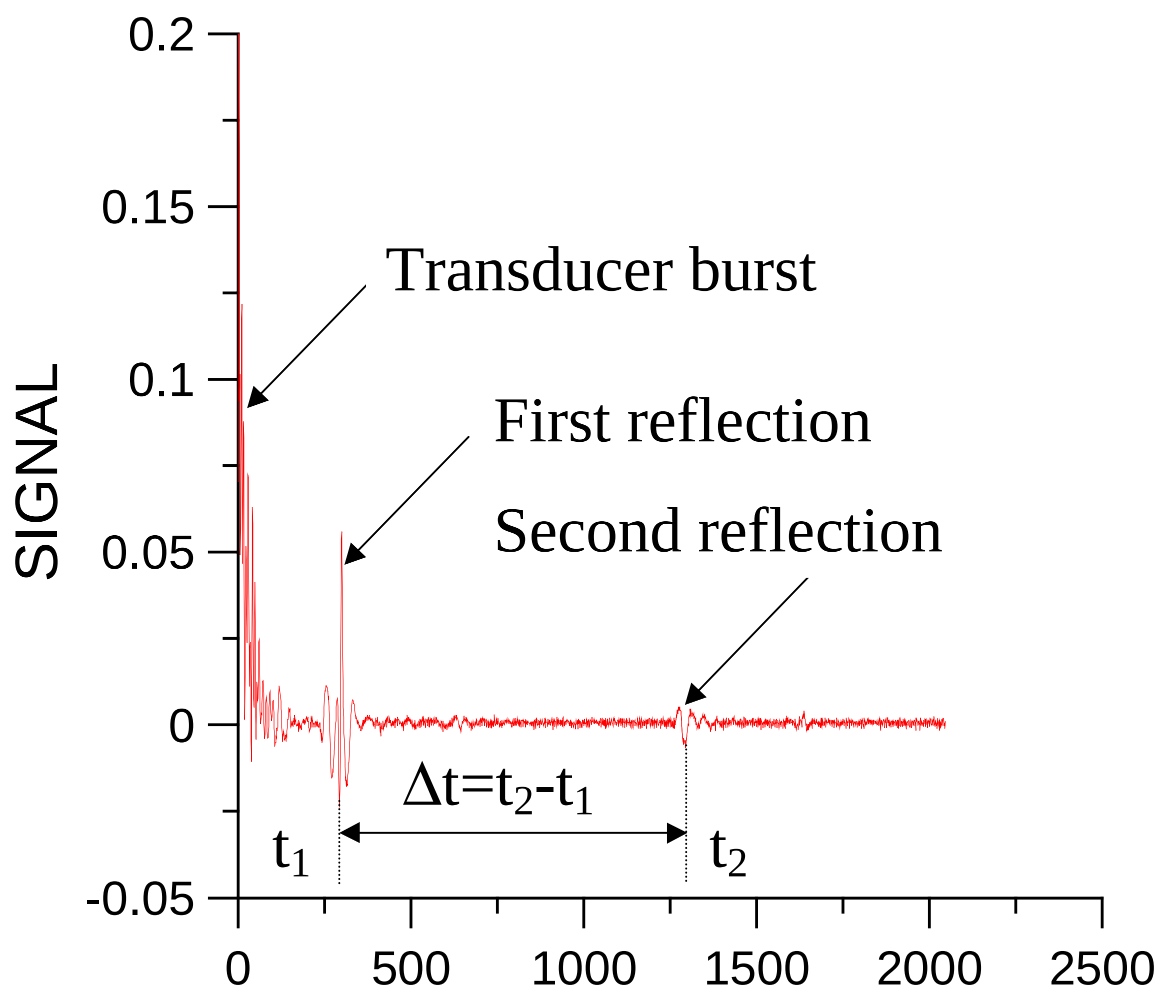


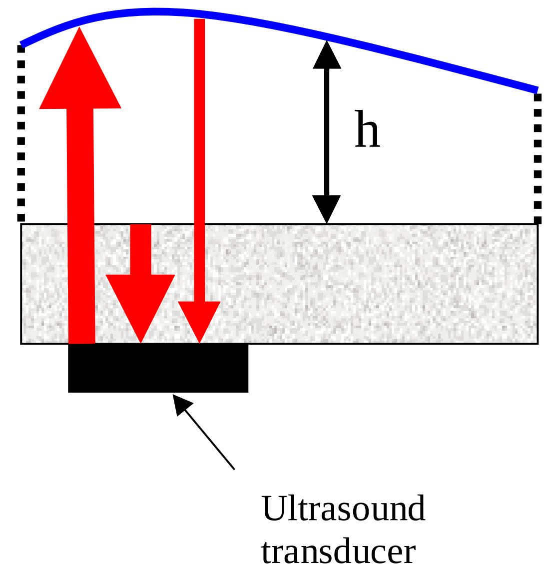
Inclination angle is 22.5°
Flow rate is 24 l/s

The red dye is injected tangentially at the surface with the velocity close to the bulk velocity. The surface image is taken with the fast-speed camera. In some locations at the surface, the dye disappears and appears again. This can be explained by the surface renewal mechanism caused by the overturning waves.

We are planning to use the dye data to estimate the turbulence diffusion coefficient in the spanwise direction.

MEASUREMENT OF THE FLOW HEIGHT WITH THE ULTRASOUND TRANSDUCER



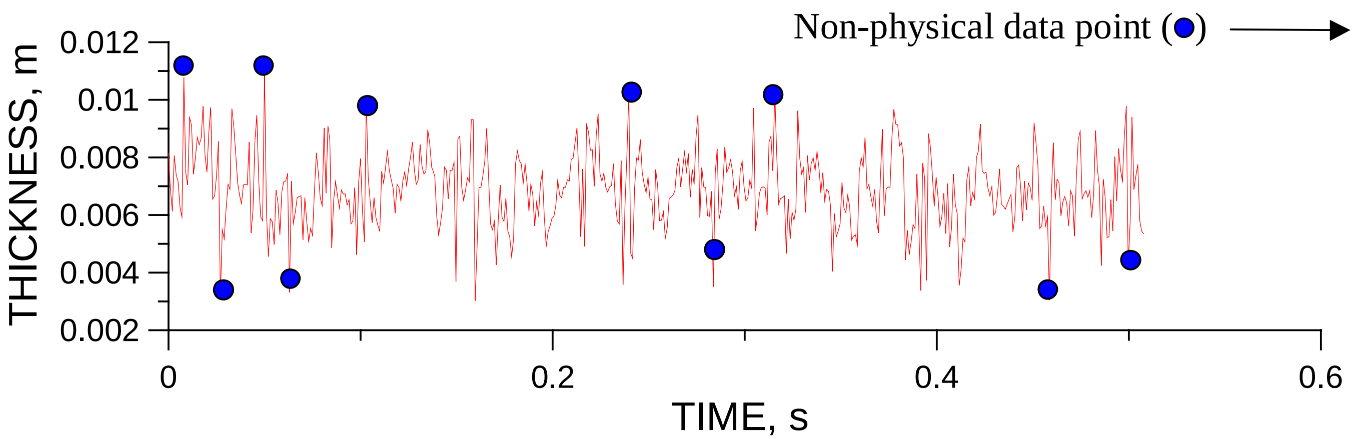


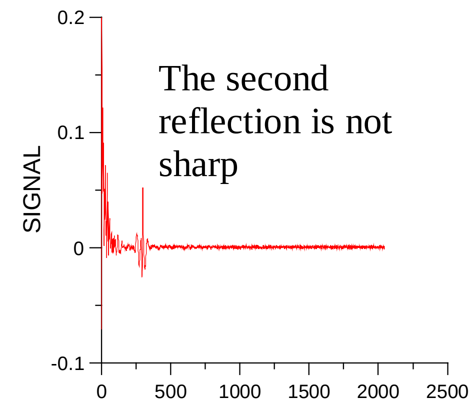
$$\mathbf{h = V \times \Delta t}$$

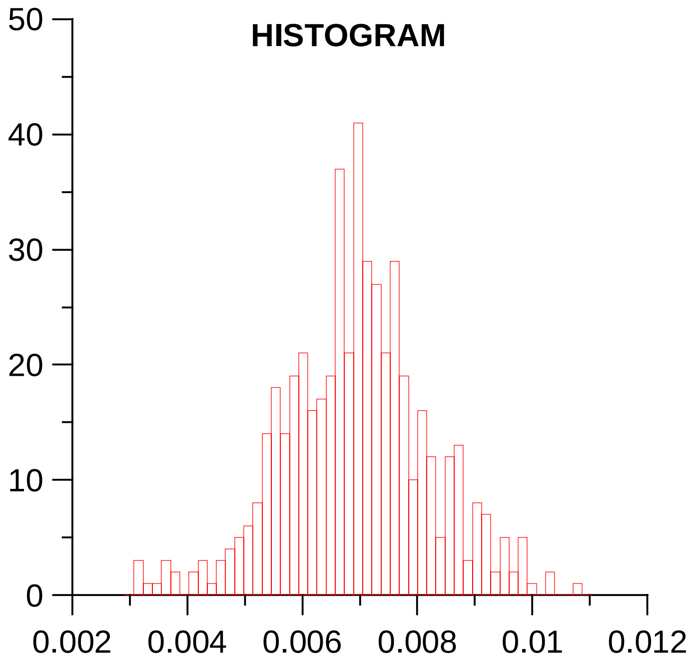
V is the ultrasound speed

Δt is the time interval between two reflections

TYPICAL TIME VARIATION OF THE FLOW THICKNESS IN A GIVEN POINT and HISTOGRAM



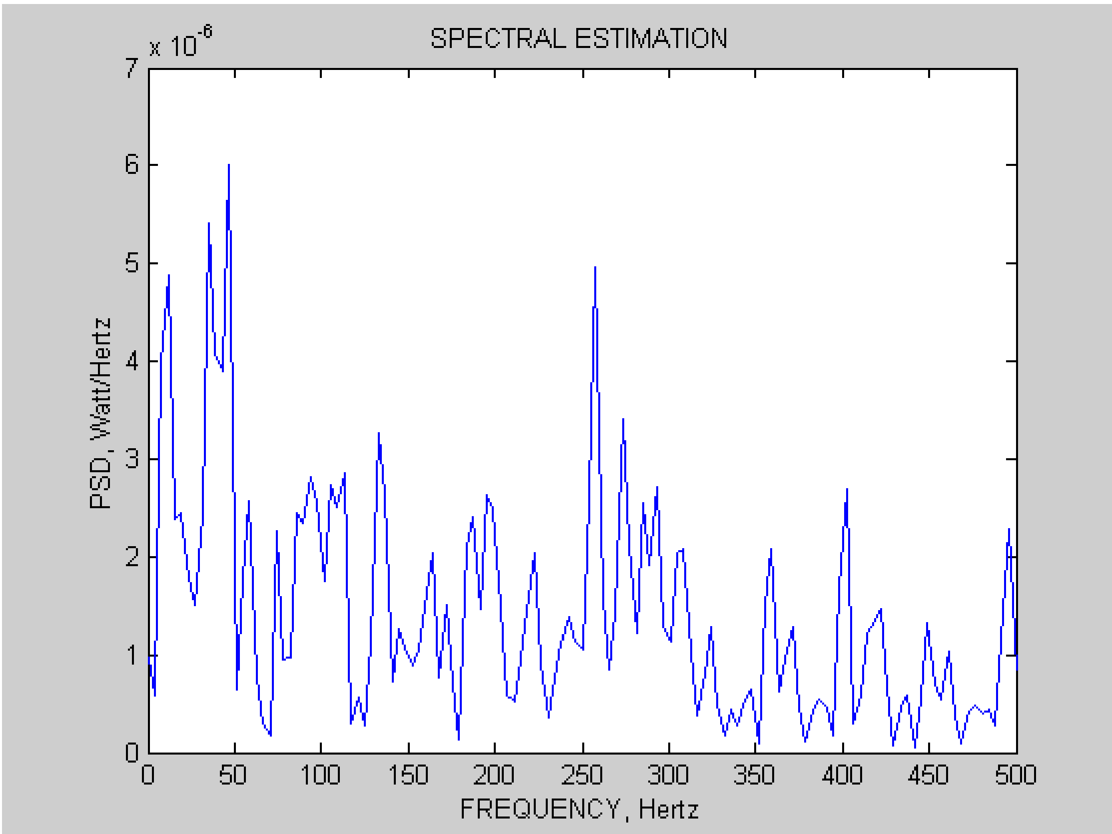




A sinusoidal type wave can be hardly viewed because of the white noise and also because of the non-physical high-frequency, high-amplitude oscillations caused by some instrumental errors. Such "bad" data points appear when the second reflection is not sharp enough. There can be two ways of improving the data quality.

- Positioning the transducer with its facial surface directly at the chute bottom
- Filtering the data using a digital filter

SPECTRAL ANALYSIS OF h(t) FROM A SINGLE DATA SET



Power Spectral Density (PSD) obtained from a single data set does not carry much information because of the random noise. Welch's averaged periodogram method: **1 data set**.

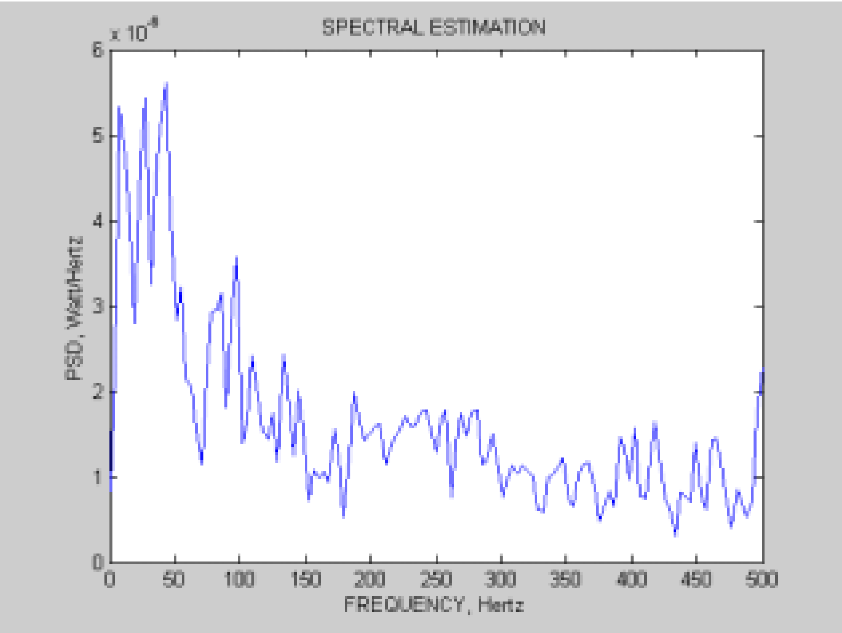
Inclination angle =30°; Flow rate = 9.5 l/s; Fully developed flow thickness = 6.15 mm

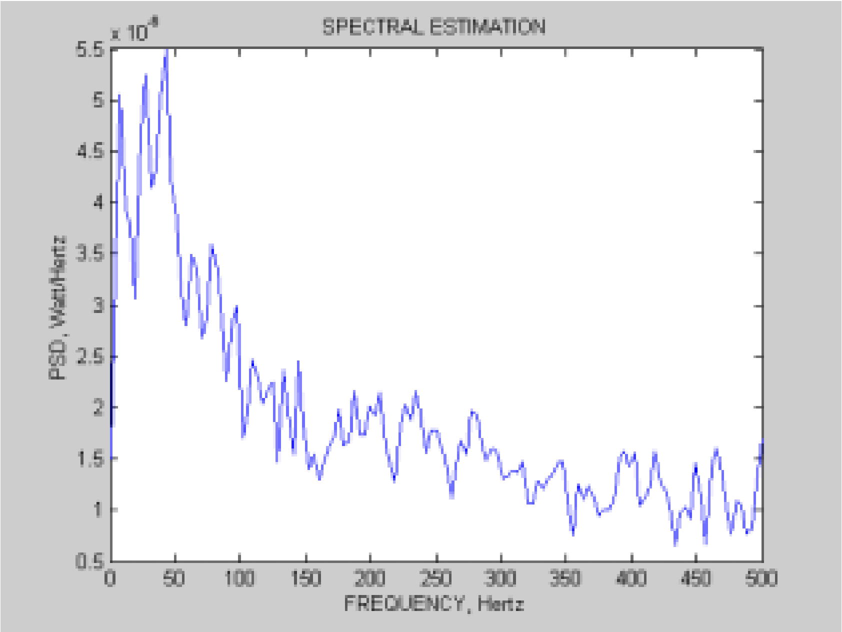
SPECTRAL ANALYSIS PROCEDURE

The goal of *spectral estimation* is to describe the distribution (over frequency) of the power contained in a signal, based on a finite set of data.

Here, Power Spectral Density (PSD) is estimated using Welch's averaged periodogram method. The signal is divided into overlapping sections, each of which is multiplied by a smooth curve called a Hamming window. This results in reducing the signal amplitude near the ends of each section. Then the FFT method is applied to each section to obtain a spectrum. After that all distributions obtained are averaged. Unfortunately, the result also looks like a noisy mess. This is because there is not enough information in the original data set to obtain a well-behaved curve. The solution is to use more original data sets and then to average all distributions. The random noise reduces in proportion to the square root of the number of the data sets.

SPECTRAL ANALYSIS OF h(t) FROM 5 AND 15 DATA SETS





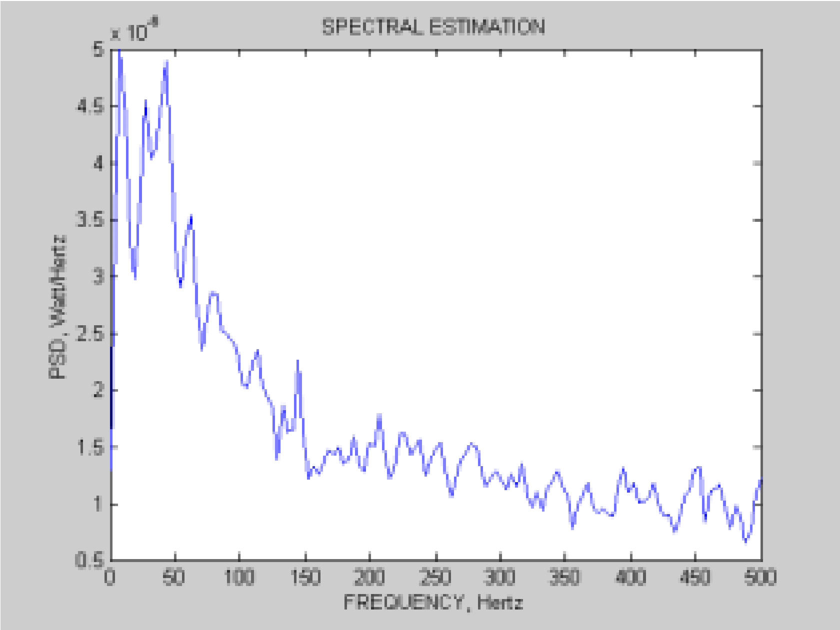
Welch's averaged periodogram method:
5 data sets.

Inclination angle =30°; Flow rate = 9.5 l/s;
Fully developed flow thickness = 6.15 mm

Welch's averaged periodogram method:
15 data sets.

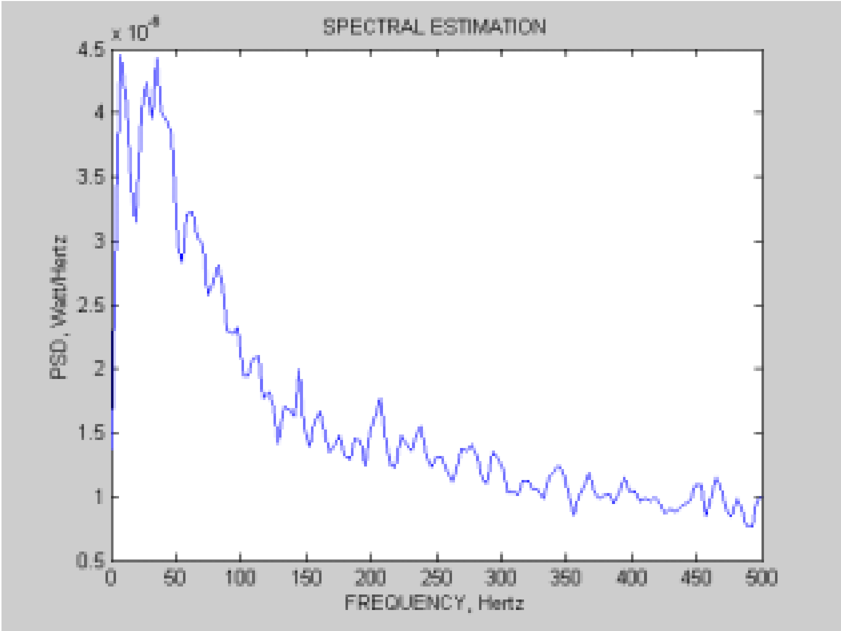
Inclination angle =30°; Flow rate = 9.5 l/s;
Fully developed flow thickness = 6.15 mm

SPECTRAL ANALYSIS OF h(t) FROM 30 AND 50 DATA SETS



Welch's averaged periodogram method:
30 data sets.

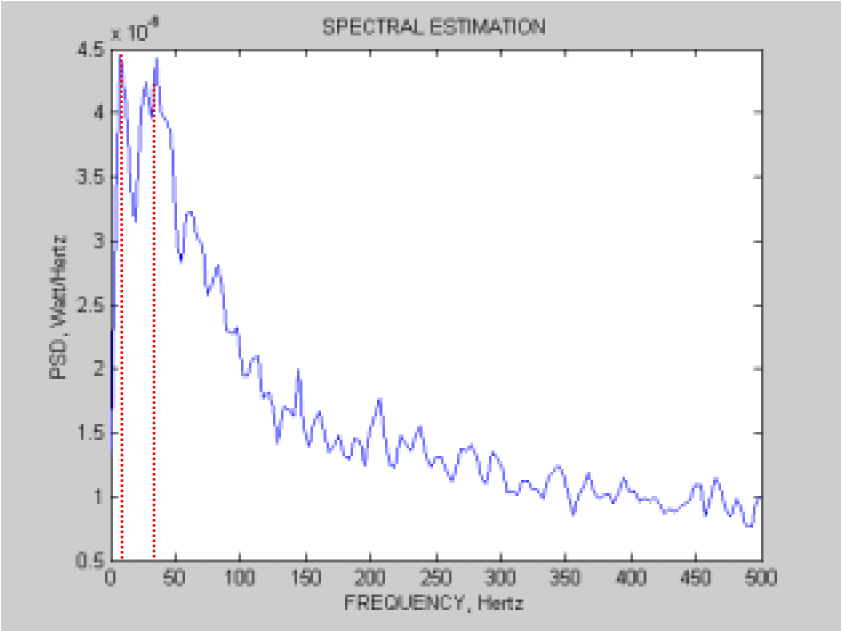
Inclination angle =30°; Flow rate = 9.5 l/s;
Fully developed flow thickness = 6.15 mm



Welch's averaged periodogram method:
50 data sets.

Inclination angle =30°; Flow rate = 9.5 l/s;
Fully developed flow thickness = 6.15 mm

SOME CONCLUSIONS FROM THE SPECTRAL ANALYSIS



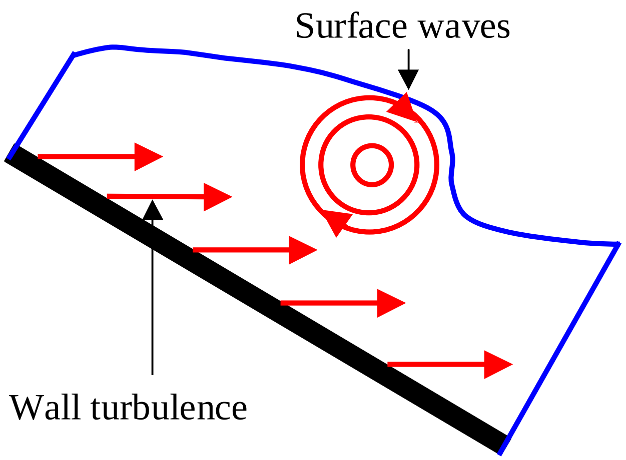
1. The spectrum is mostly contributed by harmonics with the frequencies smaller than about 150 Hertz.
2. Two big peaks in the low-frequency region can be seen: one at about 10 Hertz and the other one at about 40 Hertz.

Possible explanation ?

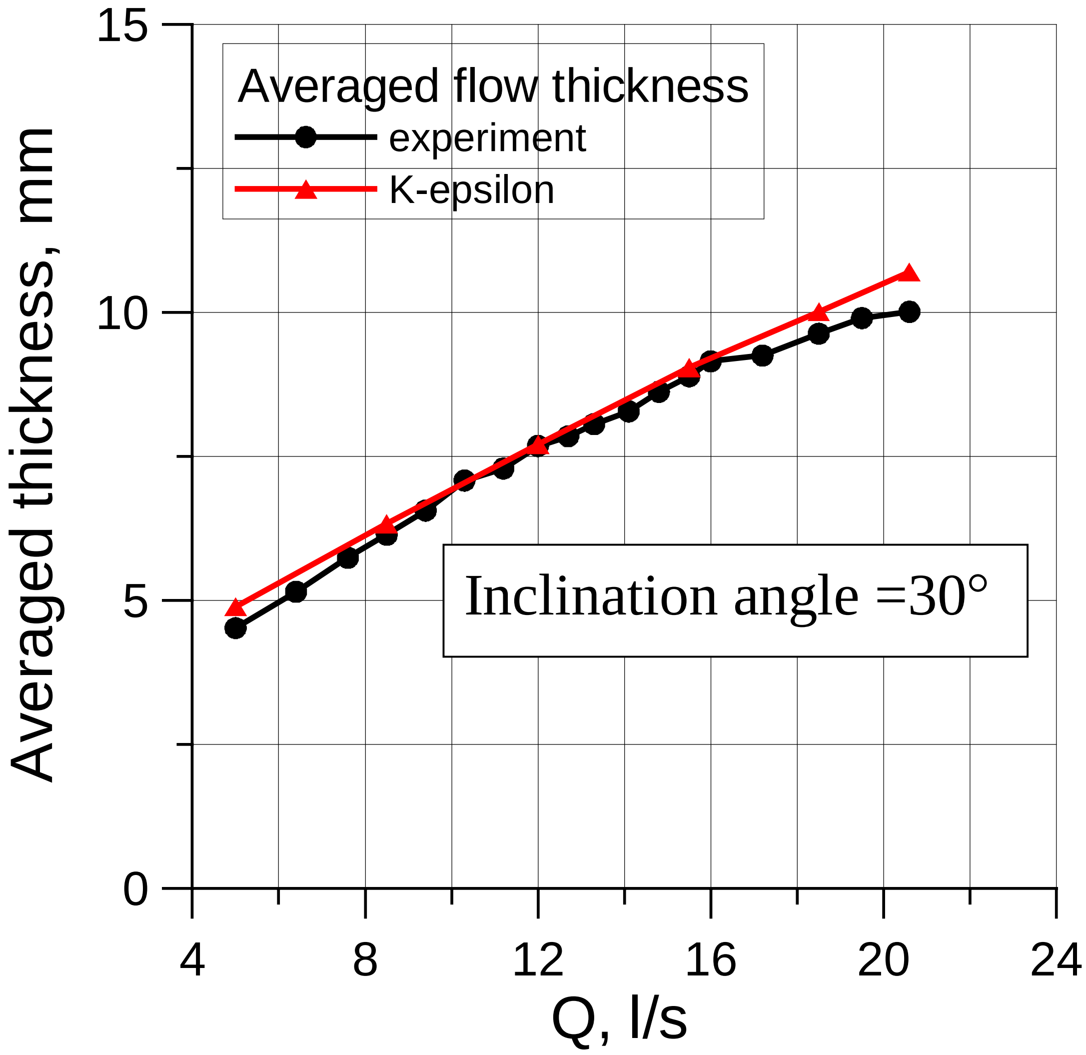
These two peaks are related to two different processes of wave generation. The first one is due to interaction of the bulk vortices with the free surface. The second one is due to the free surface instability.

Welch's averaged periodogram method:
50 data sets.

Inclination angle =30°; Flow rate = 9.5 l/s;
Fully developed flow thickness = 6.15 mm



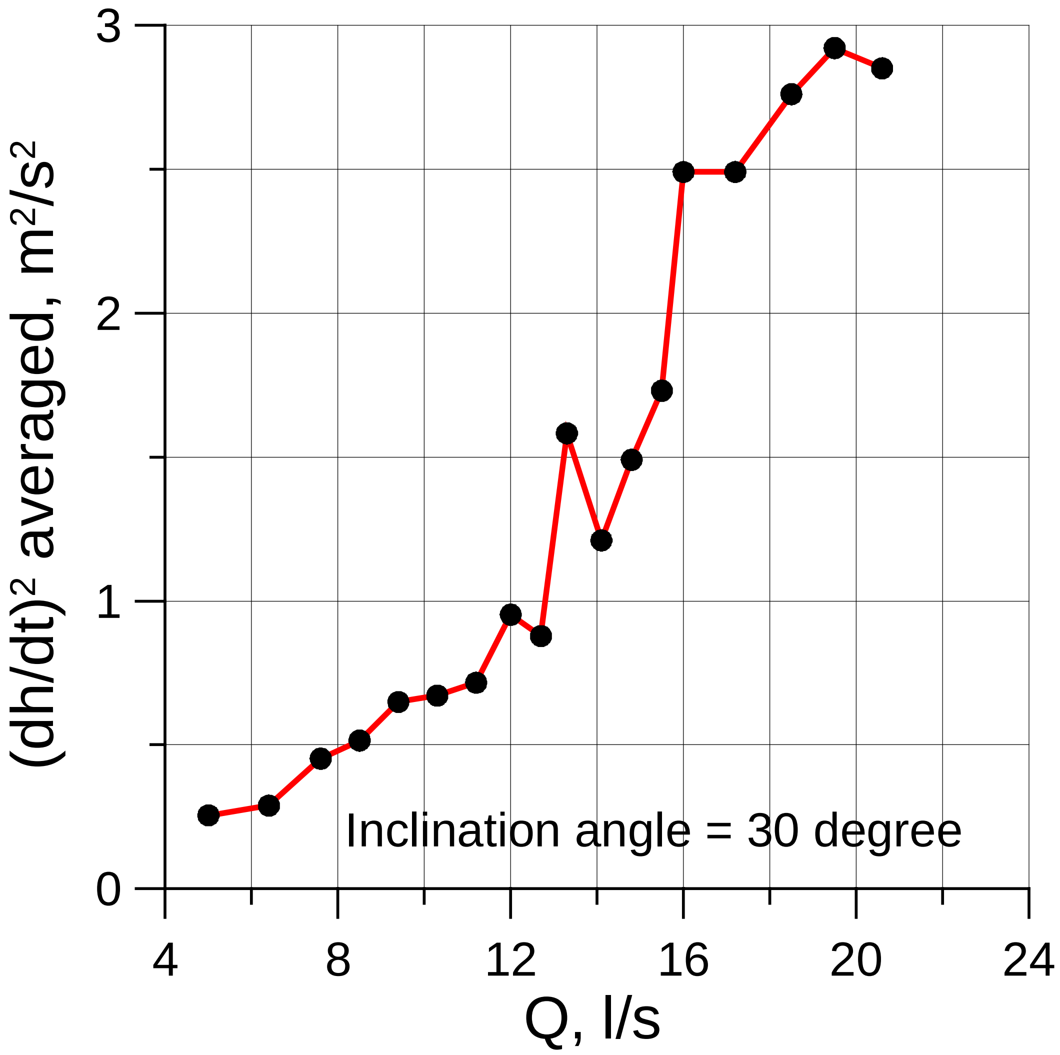
COMPARISON OF "K-epsilon" CALCULATIONS WITH THE EXPERIMENTAL DATA (flow thickness)



The K-epsilon model does not reproduce the free surface oscillations. At the same time, calculated data of the averaged flow thickness demonstrate very good agreement with the experimental data.

The model must be modified to describe the surface waviness.

$(dh/dt)^2$ AVERAGED AS A PARAMETER CHARACTERIZING THE SURFACE WAVINESS

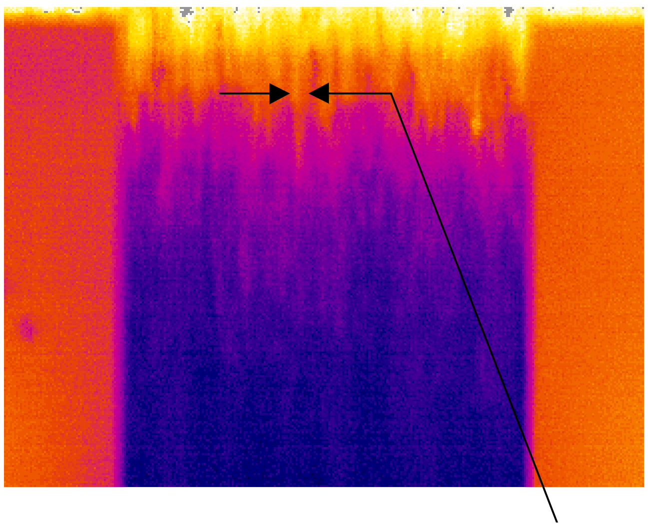


In regimes with the surface waviness and surface renewal, the intensity of the surface motion (the waviness) can be characterized by the following quantity

$$K = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{dh}{dt}\right)_n^2 .$$

This quantity has a dimension of the energy per unit mass. It is a good representation of the kinetic energy originated from the normal displacements of the free surface. The plot shows the surface waviness increase as the flow rate grows. Unfortunately, the data are not statistically reliable because the instrumental and random errors are greatly increased due to differentiating.

INFRARED CAMERA MEASUREMENTS



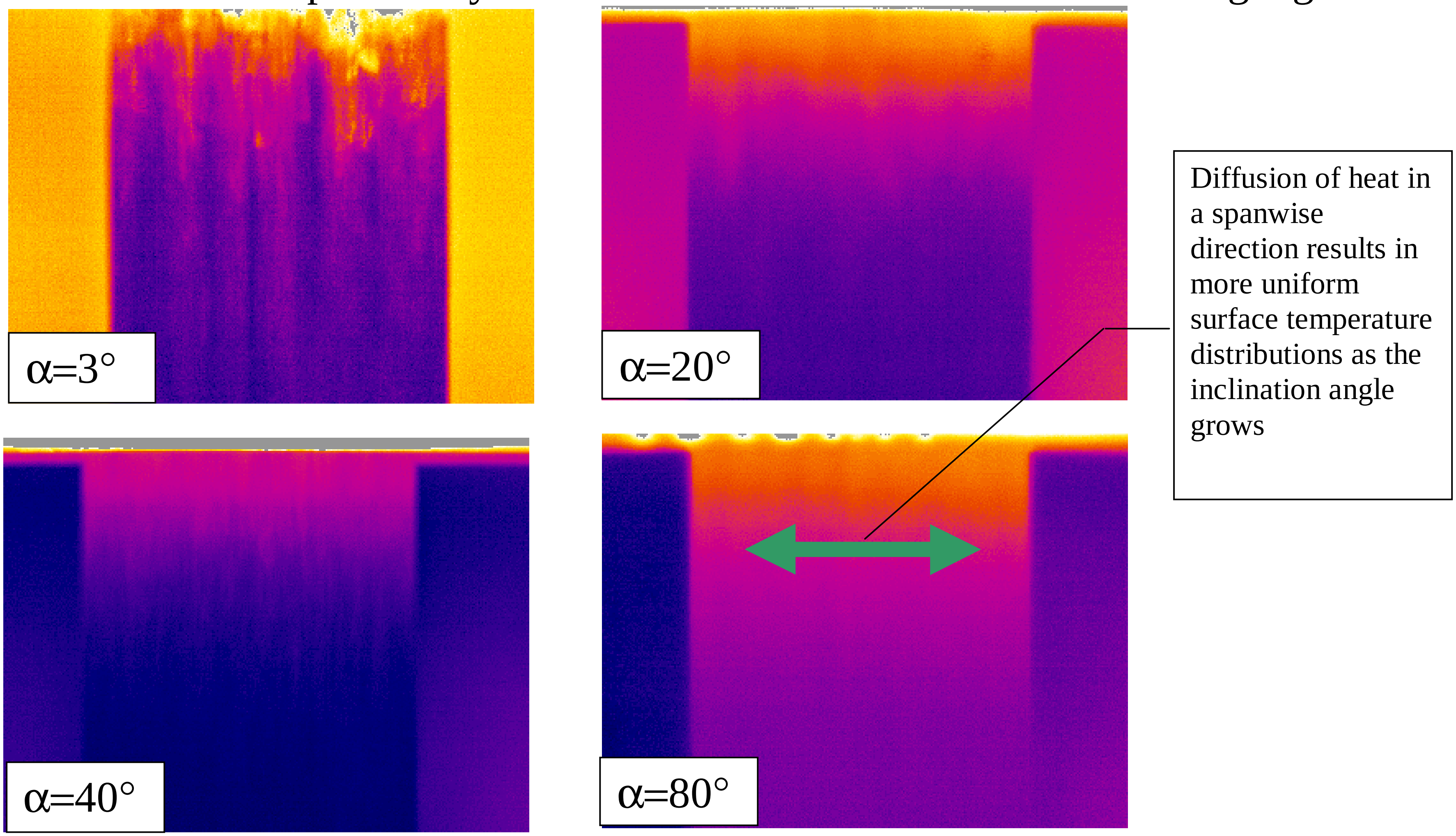
Elongated turbulent structures

IR camera image. The observation area is 10 by 12 cm that corresponds to 200 by 240 camera pixels. The measurements were done right after the heater edge (upper border of the frame). The elongated structures at the surface become poorly distinguishable at a certain distance from the heater because of the diffusion of heat in both wall-normal and spanwise direction.

The IR camera images show elongated turbulent structures stretched in the flow direction at the free surface. These structures have not been observed in low-Reynolds number DNS and in previous experimental studies of near-surface turbulence (Rashidi and Banerjee). The estimated width of these structures is from several millimeters to 1-2 centimeters. The length can reach up to tens of centimeters.

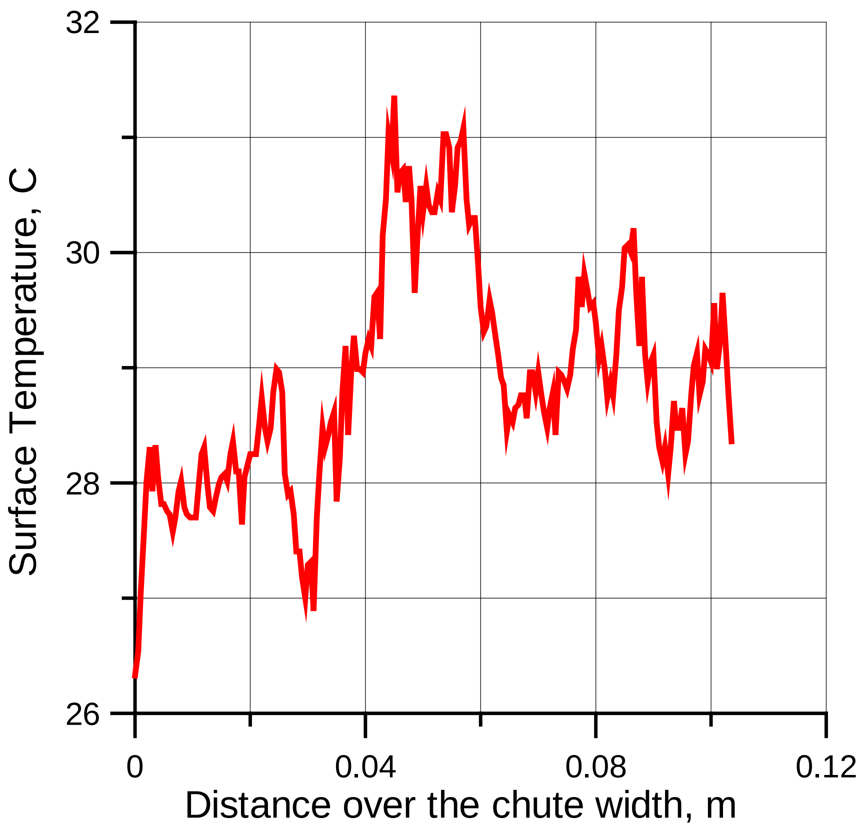
INFRARED CAMERA MEASUREMENTS

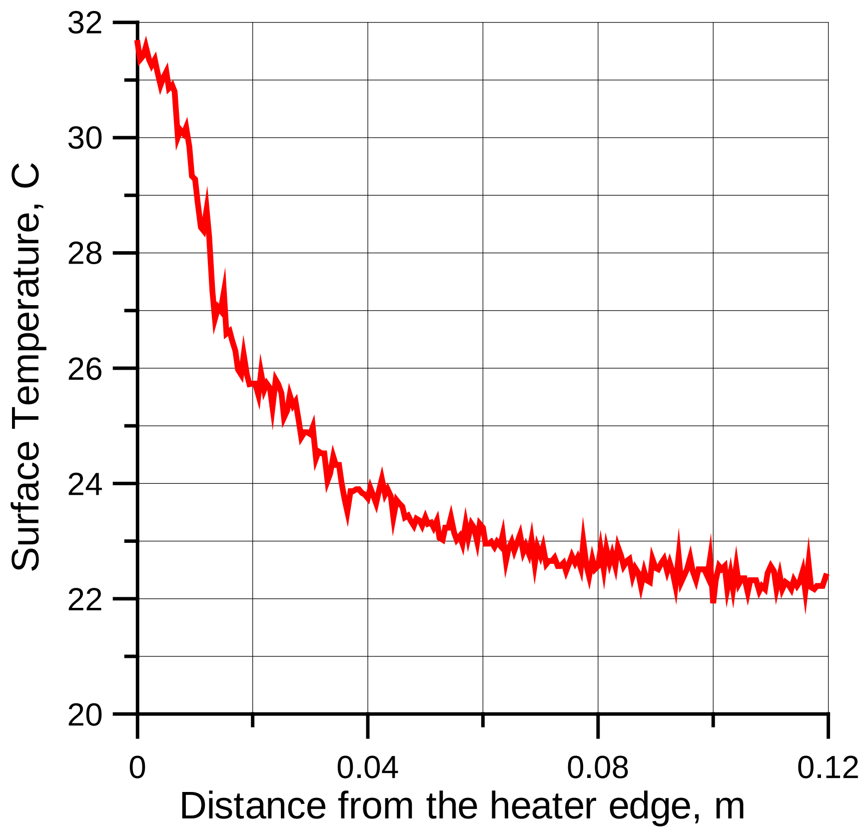
The elongated turbulent structures are better seen in IR images for shallow angles. This could be explained by more intensive diffusion as inclination angle grows.



SURFACE TEMPERATURE DISTRIBUTION

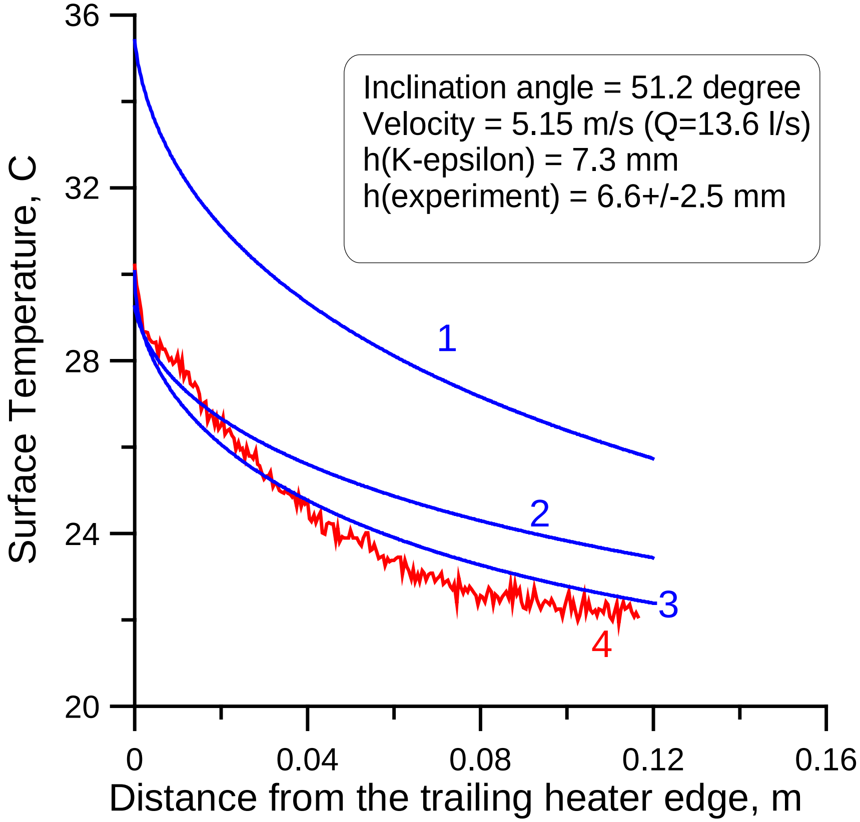
The temperature distribution is extremely non-uniform. There are "hot" and "cold" spots. The spanwise fluctuations of the temperature field are stronger than the streamwise ones.





Spanwise (left) and streamwise (right) surface temperature distribution. The inclination angle is 3°.

COMPARISON OF "K-epsilon" CALCULATIONS WITH THE EXPERIMENTAL DATA (heat transfer)



Heater power is 20 kW
Heated area is 30x30 cm^2
Experiment
Calculations

The comparison of the experimental data with the calculation shows that a reasonable coincidence can be achieved (in terms of the averaged temperature) by adjusting the turbulent Prandtl number distribution. The curve 3, which is close enough to the experimental curve, was calculated at

$$\Pr_t = 0.7(1 + \exp\{37[y/h - 0.912]\}).$$

Unfortunately, the model can not predict the local temperature non-uniformity, such as "hot" and "cold" spots.

CONCLUSIONS (related to particular flow parameters in the experiment)

1. The experimental data confirm the flow regimes with the surface renewal.

2. The most energy containing waves at the surface are those having the frequency smaller than about 150 Hertz. There are two local peaks in the spectrum at 10 and 40 Hertz, which probably stand for two different mechanisms of wave generation.

3. The surface temperature is extremely non-uniform because of the free surface oscillations.

4. The K-epsilon model provides good estimations of the averaged flow thickness and averaged temperature. The model does not resolve the surface waviness and local temperature non-uniformity.

PLANS

Experiment:

1. To reduce errors in h(t) by data filtering or/and changing the transducer position.
2. To get smoother spectrum by improving the signal quality and using more data.
3. To reduce errors in averaged $(dh/dt)^2$.
4. To conduct ultrasound measurements in a wider range of flow parameters.
5. To conduct experiments with the red dye to diagnose the flow regimes.
6. To run PIV system.
7. To conduct new IR camera measurements.

Theory:

1. To evaluate Pr_t distributions from the experimental data.
2. To conduct LES calculations.
3. To specify the K-epsilon range of applicability.