Lecture 39: Validation of LCT measurements

- Experimental Procedure
- Validity of the Semi-infinite Solid Mode
- Validation
- Law of the Wall
- Flat Plate Correlation
- Videos

Previous Next

For determination of the heat transfer coefficient from a transient experiment, the test section is heated to a constant temperature followed by cooling under forced flow conditions. The mainstream flow is started by turning on the digitally controlled blower. Fluid velocity is recorded at the inlet of the test section by the pitot static tube. The measurement indicates that the transient period for establishing the flow is around 3-5 seconds, reckoned from the start of the blower. The sequence of images of the LCT sheet is recorded after the full flow rate is reached. The rate of cooling of the surface of the heated test section is recorded as a set of color images. Images obtained in a transient experiment, with one solid rib mounted on the test surface is shown in Figure 6.6.

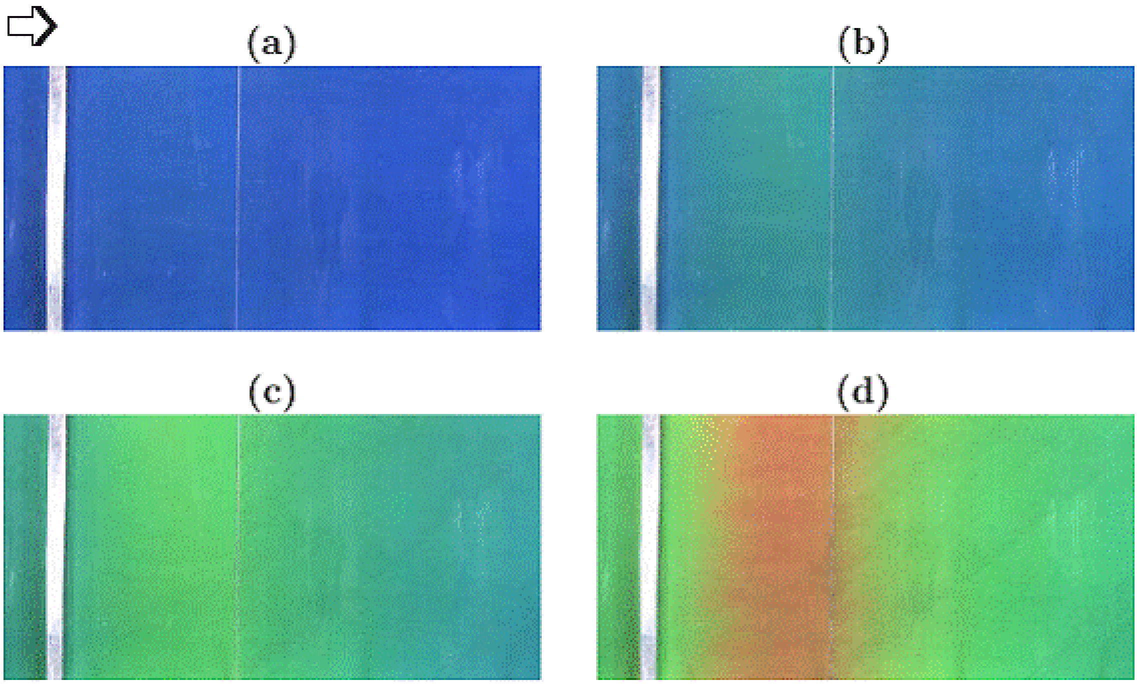

Figure 6.6: An image sequence showing changes in color during the cooling of a plate downstream of a solid rib (arrow indicates the flow direction); figures (a) to (d) are arranged in an increasing time sequence.

Here, red indicates the coldest region followed by green, yellow and blue respectively for higher temperatures. Initially the plate is heated up to the clearing point temperature and correspondingly the LC sheet appears to be uniformly blue. Once the flow is established, the surface cools under forced convection conditions. A gradual change in temperature occurs with time. Subsequent images (Figures 6.6 (b-d)) show the color-temperature distribution at later times. The effect of a reattaching boundary layer in to cool preferentially the surface downstream of the rib. Equivalently, it is a region of high heat transfer (coefficient). Streaks of yellow and red indicate zones of high heat transfer as clearly revealed in Figure 6.6(d) within the reattachment region. Comparatively higher temperatures upstream of the rib points towards low heat transfer where the flow is stagnant within the recirculation zone. Overall, the images show that LCT can be used as a visualization tool for qualitative information. These data (images) are subsequently digitized frame by frame. The history of color distribution at each pixel yields the temperature history of the test surface.

Previous Next

The temperature recorded by the liquid crystal sheet can be equated to the temperature of the thin aluminum plate mounted on the surface of the upper bakelite sheet. Owing to its high thermal conductivity and small thickness, the temperature drop through the aluminum sheet can be taken to be negligible. This temperature, as a function of space and time will then prevail over the bakelite sheet as well. The Bakelite sheet serves as a semi-infinite solid with experimentally determined wall temperature boundary conditions.

For a semi-infinite solid, the 1-D transient heat conduction equation is given as

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2}$$

The related wall boundary condition is

$$-k \frac{\partial T}{\partial y}\bigg|_{y=0} = h[T(0,t) - T_\infty]$$

The analytical solution of the diffusion equation is

$$\frac{T_{w,i} - T_w(t)}{T_{w,i} - T_b} = 1 - \exp\left(\frac{h^2 \alpha t}{k^2}\right) \operatorname{erfc}\left(\frac{h\sqrt{\alpha t}}{k}\right)$$

Here, $T_w(t)$ is the surface temperature at time t, T_b is the bulk temperature inside the channel, $T_{w,i}$ is the initial surface temperature, h is the convective heat transfer coefficient, a is the thermal diffusivity and k is the thermal conductivity of the Bakelite plate. The local bulk temperature can be determined by interpolating the temperatures at the inlet and the exit of the test section.

The transient non-dimensional temperature variation of the test surface can be curve-fitted by using the least square approximation where the local heat transfer coefficient h is a parameter. Parameter estimation falls in the general class of inverse techniques and the above formulation classifies as an inverse transient method.

- Click here to read a fuller version of the inverse heat transfer procedure.

Validity of the Semi-infinite Solid Model

The transient technique for the determination of the heat transfer coefficient is mainly based on the model of heat conduction in a semi-infinite solid. Schlutz and Jones (1973) have provided criteria for the validity of the semi-infinite solid assumption. Specifically, they require that the minimum thickness of the material should be greater than $4\sqrt{\alpha t}$ where α is the thermal diffusivity, and *t*, the total time. The maximum duration of our experiment is 80 seconds and the selection of the specimen material (Bakelite) and thickness do satisfy the criteria. A simple calculation with the thermophysical properties of Bakelite will reveal that the maximum permissible penetration time of the 25 mm thick Bakelite plate is around 340 seconds, much larger than the total duration of transient run.

The temperature variation of the top and bottom surfaces of the Bakelite plate have been recorded by means of the data acquisition card for one of the transient experiments (Figure 6.7).

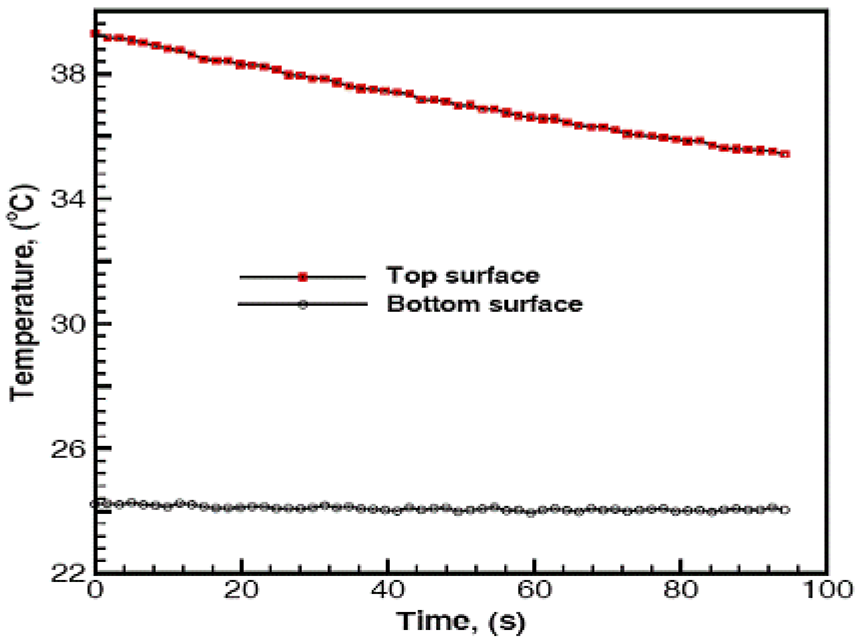

Figure 6.7 Temperature variation in the Bakelite plate during the transient run.

It is seen that the lower surface remains at practically a constant temperature during the cooling of the test surface. Thus, the temperature front is well-contained within the Bakelite sheet of finite thickness, confirming the validity of the semi-infinite solid approximation.

Previous Next

Validation

The validation of the transient LCT approach in the calculation of the Nusselt number has been established from flat plate experiments for a turbulent boundary-layer. In addition, it is possible to check the energy balance by comparing wall heat flux estimated by liquid crystal thermography with the heater input on one hand and the enthalpy outflow on the other. In the experiments conducted, the energy balances obtained where within 2-5% of one another.

Law of the Wall

The local Nusselt number obtained from LCT in the main flow direction at Reynolds numbers of 13400 and 32100 are compared with those using correlations for a smooth channel in Figures 6.8 and 6.9 respectively. The agreement between experiments and the well-established correlations is quite good, the maximum deviation being approximately 8%. Overall, Figures 6.8 and 6.9 reinforce the validity of the LCT approach for the determination of the heat transfer coefficient.

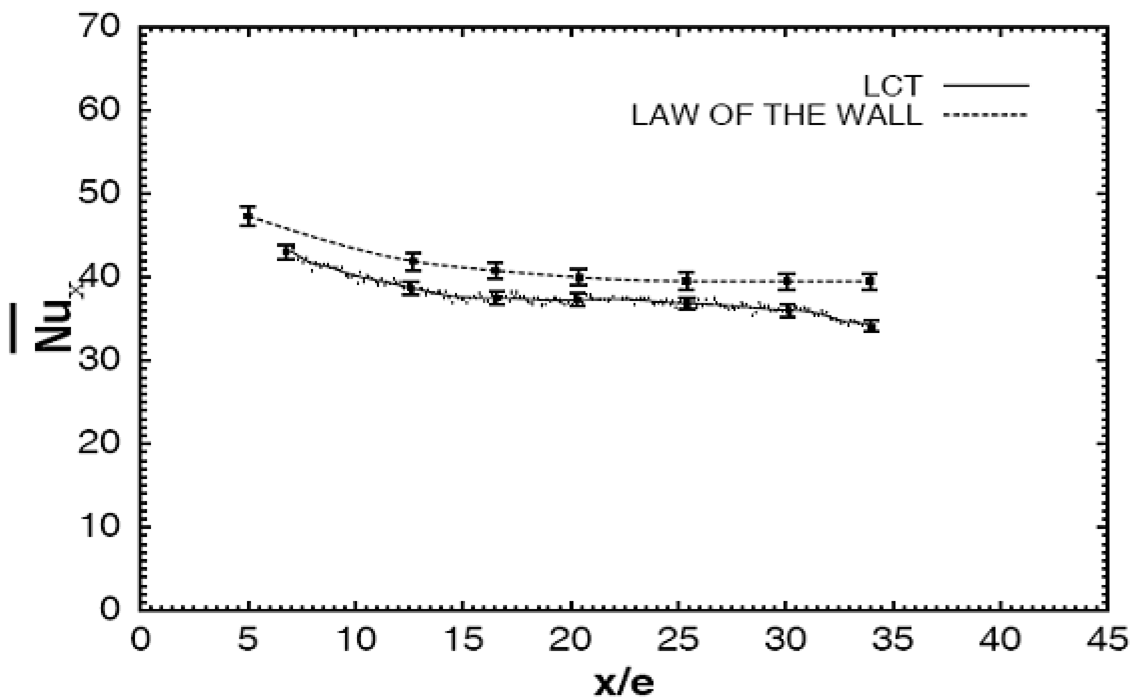

Figure 6.8 Comparison of Nusselt number variation determined using LCT with that for a smooth channel at Re=13400. The Nusselt number reported is an average calculated in the direction normal to that of the main flow. The streamwise distance is presented in a suitably dimensionless form.

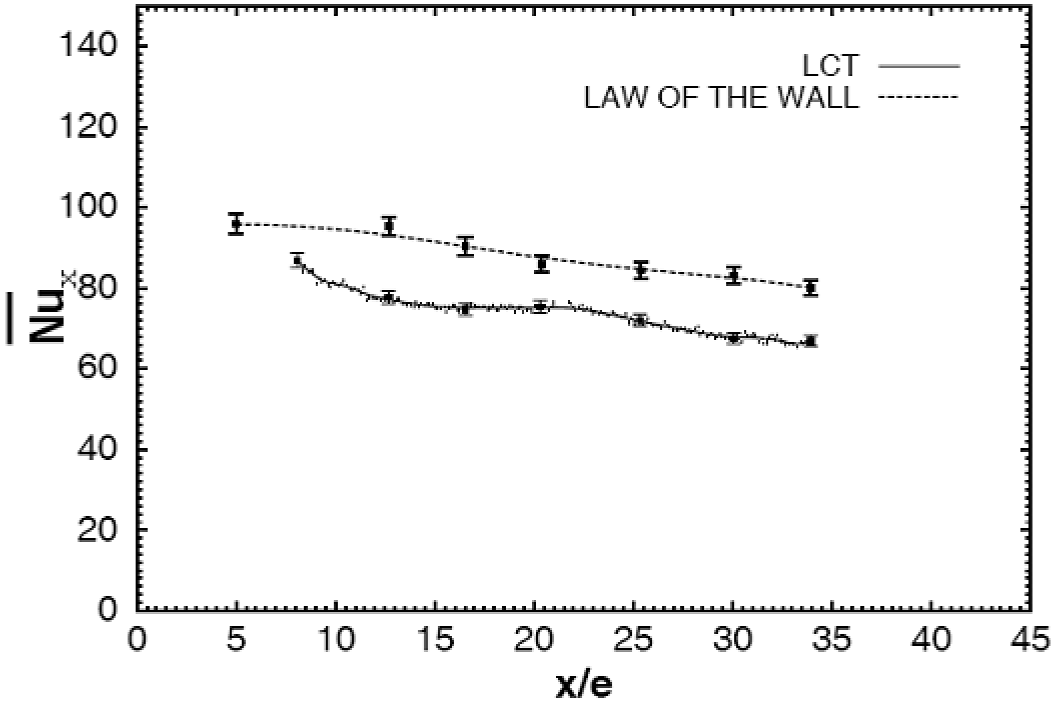

Figure 6.9 Comparison of the local Nusselt number variation determined using LCT with that for a smooth channel at Re=32100. The local Nusselt number reported is an average calculated in the direction normal to that of the main flow. The streamwise distance is presented in a suitably dimensionless form.

Previous Next

Flat plate correlations

The results have also been validated against the flat plate correlation

$$Nu(x)=0.0287\ Re_x^{\ 0.8}\ Pr^{\ 0.4}$$

for Nusselt number distribution in turbulent flow (Kays and Crawford, 1993). Figure 6.10 shows this comparison at Reynolds numbers of 13,400 and 32,100. The experimental data and the correlation match well, though with an offset. There is an associated difficulty in proper determination of the origin for the channel flow. The offset can be attributed to the error in the calculation of the streamwise distance.

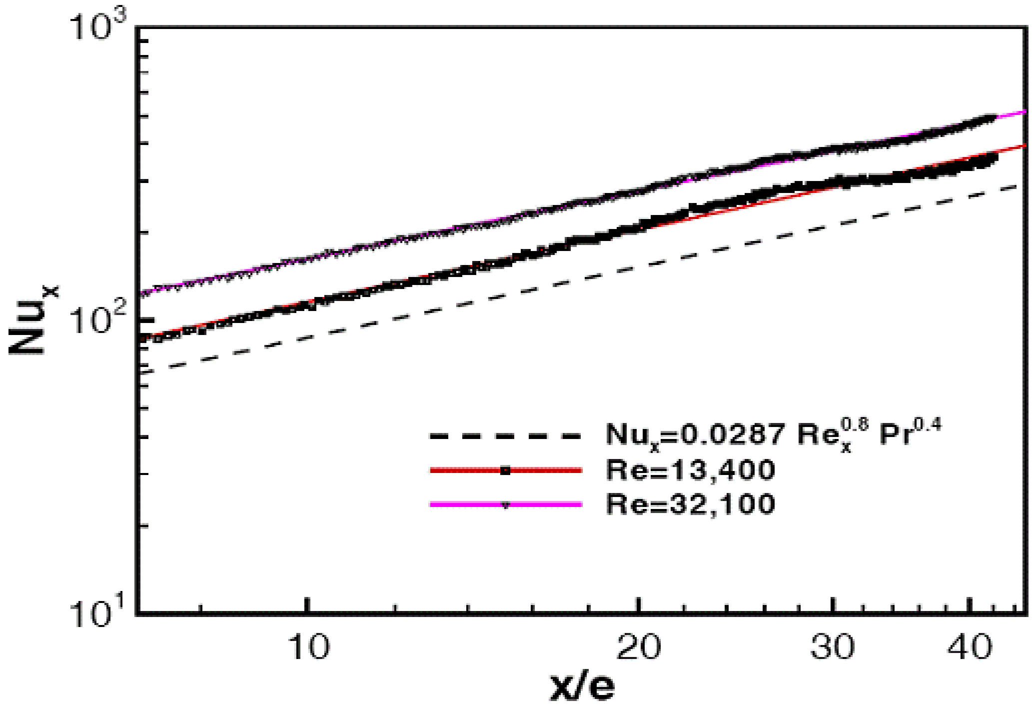

Figure 6.10 Comparison of the local Nusselt number as a function of distance from LCT measurement with the flat plate correlation (Kays and Crawford, 1993) at Re=13400 and 32,100. The symbols correspond to the experimental data and the line represents best curve through the data.

Previous Next

Table 6.1 Exponent of Reynolds number in the Nusselt number correlation determined from experiments at various Reynolds numbers

	Correlation[a]	Present Experiment [b]			
Re		13,400	22,600	32,100	40,800
m	0.8	0.81	0.73	0.77	0.87

[a] $Nu=0.0287Re^{0.8}Pr^{0.4}$

[b] $Nu=C.Re^{m}Pr^{n}$

The exponent of Reynolds number appearing in the Nu(x) correlation are reported in Table 6.1. The average exponent of the Reynolds number from the experiment is equal to 0.795, against a value of 0.8 appearing in the correlation. The maximum deviation of the average exponent of the Reynolds number in the smooth channel experiment from LCT against the flat plate Nusselt number is within $\pm 0.5\%$. These checks confirm the accuracy of the LCT technique in heat transfer.

- Click here to read a fuller version of heat transfer measurements and the extent of enhancement obtainable in ribbed surfaces.

Video 1 shows a heat transfer experiment for flow over a flat plate. The plate is pasted with a liquid crystal sheet. The plate (seen in a plan view) is also initially heated and at a uniform temperature. Hence, the liquid crystal sheet appears blue. The experiment is started when air flow (from left to right) is initiated. The incoming air temperature is lower than that of the heated surface. At the same time, the heater connected to the flat surface is turned off. Under the influence of air flow, the surface cools with time. Owing to the formation of a thermal boundary layer, the cooling rate closer to the leading edge is faster than that to the right. Hence, the LCT sheet changes color from blue to red – first on the left side and then at the right.

Previous Next

Module 6: Liquid Crystal Thermography

Lecture 39: Validation of LCT measurements

Video 2 shows a heat transfer experiment for flow over a flat plate with a rib of square crosssection placed closer to the upstream corner. The plate (seen in a plan view) is pasted with a liquid crystal sheet. The plate is also initially heated and at a uniform temperature. Hence, the liquid crystal sheet appears blue. The experiment is started when air flow (from left to right) is initiated. The incoming air temperature is lower than that of the heated surface. At the same time, the heater connected to the flat surface is turned off. Under the influence of air flow, the surface cools with time.

Owing to the formation of a thermal boundary layer, the cooling rate closer to the leading edge is faster than that to the right. The presence of the rib disrupts the hydrodynamic boundary layer, leading to vortex generation downstream. The vortex is also transported with the main flow. Hence, the heat transfer rates just downstream of the rib are very large and the plate cools very rapidly. This is seen from the red color that appears rapidly in this region. Elsewhere, the plate cools at a modest pace. In any case, the overall heat transfer rate for the plate with a rib is much greater than one without a rib (shown in video 1).

Previous Next