Eidgenössische Technische Hochschule Zürich
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Laboratory for Energy Conversion

Report

Experimental Methods For Engineers

Heat Transfer Analysis Using Thermochromic Liquid Crystals

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Chapter 1

Introduction

In turbomachines very high temperatures are desired to increase the efficiency of the whole system. However, especially downstream of the combustion chamber, fluid temperature can rise above the melting point of the material used for the blades. Special precautions have to be applied as for example coating, thin film cooling and convective cooling. This experiment focusses on internal convective cooling and tries to determine the heat transfer coefficient α by using thermocromic liquid crystals (TLC). Since it remains difficult and costly to measure α inside a turbine blade a ducting channel as an experimental model with comparable non-dimensional characteristic numbers is used. Although the setup allows to determine heat coefficients in sections with different obstacles, this experiment will only focus on v-shaped obstacles causing a turbulent flow.

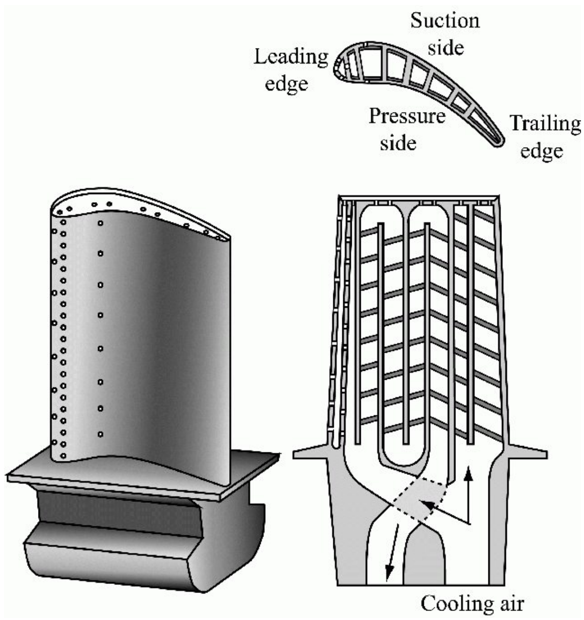


Figure 1.1: Internal Cooled Turbine Blade

Chapter 2

Laboratory Description

2.1 Experimental Setup

The experiment consists of a tank filled with warm water at $T_i = 51°C$ and a test section connected to it as shown schematic in Figure 2.1. The water from the reservoir is constantly pumped through the test section so that all components should roughly be heated up to T_i.

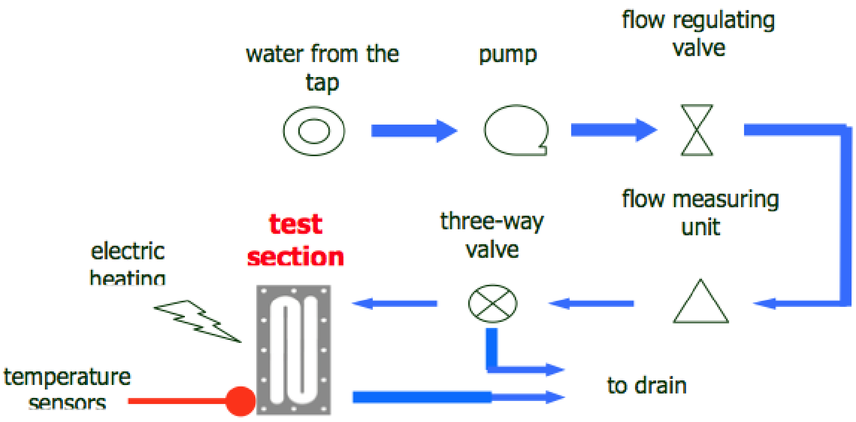
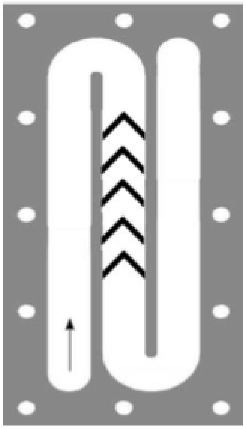


Figure 2.1: Schematic Setup of the Experiment

The test section itself contains an aluminum back plate with a TLC-sheet on its surface. In the cooling channel some v-shaped obstacles are arranged to cause a turbulent flow. The front plate is made out of plexiglas allowing the camera to capture pictures of the TLC-sheet.



(a)

(b)

Figure 2.2: Testsection (a) with obstacles (b) schematic

2.2 Experimental Procedure

As mentioned above water is pumped through the closed loop for about an hour to obtain the uniform temperature $T_i = 51°C$ in all components. Measurements start as soon as the three-way valve is opened (t=0) and a cold water pulse runs through the test section at $T_\infty = 10°C$. A CCD camera linked to a computer captures the change of color of the liquid crystals foil caused by the temperature drop. A simultaneously started MATLAB file saves the camera's 100 pictures and post processes the data.

Chapter 3

Theory

3.1 Model Building

In order to measure the local heat coefficient α a valid experimental model is required. To create a model which performs similar to the real heat exchange inside a blade non-dimensional characteristic numbers have to match. Although a turbine blade is internally cooled with air and the presented model uses water, a matching Reynolds number $Re = \frac{\rho v L}{\mu}$ yields in equitable flow conditions. However also Prandtl number $Pr = \frac{\nu}{\alpha}$ and Nusselt number $Nu = \frac{\alpha L}{\lambda}$ have to match in order to guarantee equal thermal conditions and conductivity. Finally another simplification is made by supposing only one-dimensional heat transfer to be relevant.

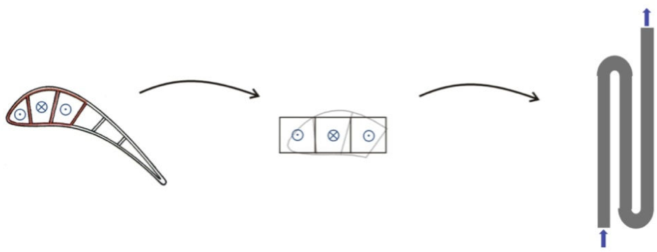


Figure 3.1: From Blade to Experimental Model

3.2 Heat transfer

The heat transfer coefficient α is determined from the unsteady one-dimensional heat conduction equation. The assumption for one-dimensional heat transfer is valid, because we consider only a very short time period and because we have only the thickness of the Aluminium plate as relevant geometric parameter, the other dimensions are in comparison very large. The time constant is given in equation 3.1

$$t_{max} = \frac{L^2}{a} = 0.9983\ s \tag{3.1}$$

with a the thermal diffusity defined in equation 3.2 and $L = 10\ mm$.

$$a = \frac{\lambda}{\rho c_p} = 0.10016 \cdot 10^{-3}\ m^2/s \tag{3.2}$$

where for Aluminium $\lambda = 238\ W/mK$, $\rho = 2700\ kg/m^3$ and $c_p = 880\ J/kgK$.

The basic one-dimensional conduction equation is shown in equation 3.3.

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} \tag{3.3}$$

To solve this equation, we need to specify initial and boundary conditions as given in the following:

$$T(x, t = 0) = T_i$$

$$T(x \to \infty, t) = T_i$$

$$\lambda \left.\frac{\partial T}{\partial x}\right|_{x=0} = \alpha(T_\infty - T(0, t))$$

where $T_i = 51°$ is the initial temperature and $T_\infty = 10°$ the fluid temperature. The solution of the differential equation is evaluated at $T(x = 0, t) = T_s$ and can be seen in equation 3.4.

$$\frac{T_s - T_i}{T_\infty - T_i} = 1 - \exp\left(\frac{\alpha^2 at}{\lambda^2}\right)\operatorname{erfc}\left(\frac{\alpha\sqrt{at}}{\lambda}\right) \tag{3.4}$$

In the measurement, we obtain the surface temerature in function of the time. As we want to determine α, we have to solve this equation but it is not linear in α and can not be solved explicitely. Therfore the delivered MATLAB file calculates the solution numerically.

3.3 Thermochromic Liquid Crystals (TLC)

With the help of Thermochromic Liquid Crystals (TLC), the surface temperature is visualized. TLC react to change of temperatures by changing their colors. This substance shows properties between a crystalline solid and an isotropic liquid.

The long chain organic molecules are aligned in a certain direction. In order to reach a dense packing, the molecules are arranged with a slight twist. On a larger scale, this leads to a helical orientation. This helix has a pitch (distance over which molecule rotates over 360°). Light hitting this structure is transmitted and reflected. Only the component of the light which has circular polarization with the same hand sign as the helix direction is transmitted, while all others are reflected. In consequence, when white light hits the structure, only one particular wavelength is reflected.

As the temperature changes, the helical structure varies. Increasing the temperature leads to two effects: thermal expansion of the helice which increases pitch and faster twist which decreases twist. The second effect is usually dominating. This results in a diminution of the molecule and a color change to shorter wavelengths.

In our experiment we use TLC with a temperature range from 35°C to 37°C. When the temperature is out of this range, the crystals appear black. Before the actual experiment, a calibration has to be done to allocate the different colorings to a particular temperature, which has been already done for us.

Chapter 4

Measurements And Results

4.1 Calibration process

As mentioned above the TLC had to be calibrated. This is quiet a time-consuming procedure, because the assumptions is made that the temperature change proceeds quasi-stationary implying that after each step thermal equilibrium is reached. RGB-data from the camera is converted to HSI and after polynomial interpolation the Hue-value correlates with the temperature as shown in figure 4.1.

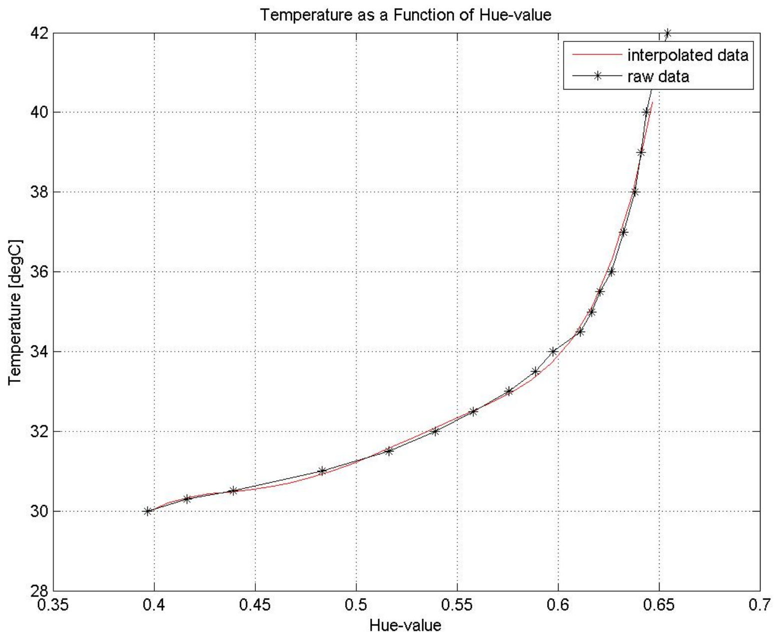


Figure 4.1: Temperature as Function of Hue Value

4.2 Measurements

The measurements we took did not yield to any meaningful result, because the camera didn't record the propagating front of cold water and thus no change in color was observed.

4.3 Qualitatively Correct Results

However the advisor provided us with reasonable results from a previous run of the experiment shown in figure 4.2 below. The camera took 100 pictures but only frame 1 to 12 depict a change in color. It seems like the cold water pulse already passed the test section and only the last part of the temperature drop is represented.

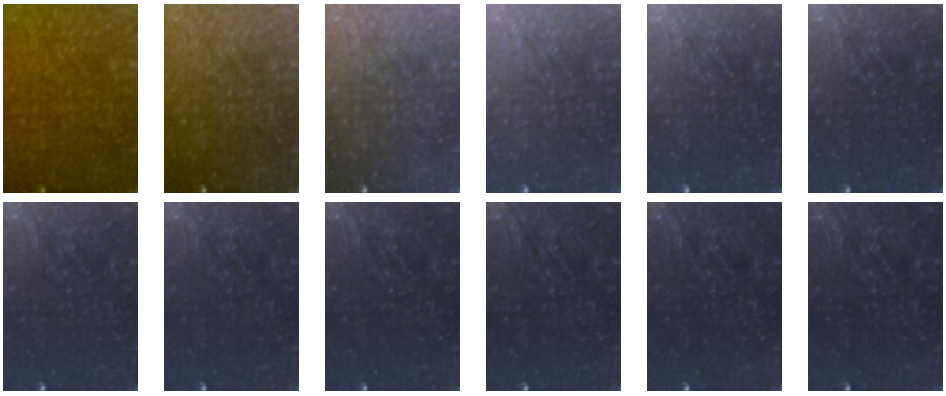
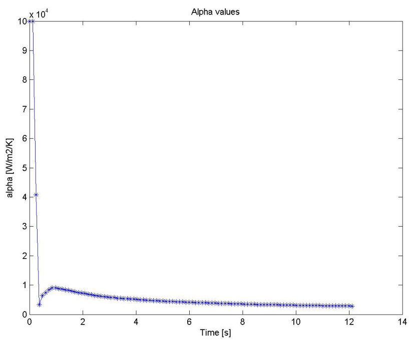
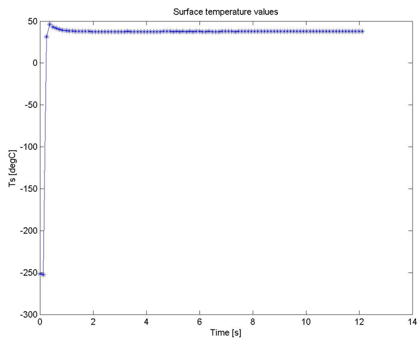


Figure 4.2: Change of Color Picture 1 to 12

Eventually the MATLAB script computed the heat transfer coefficient α and the surface temperature T_s and plotted the values in function of time displayed in figure 4.3(a) and figure 4.3(b). Apparently initial conditions for the computation are defined wrong yielding to very high values of α and very low temperatures at the beginning of the experiment. Between $t = 0.4\ s$ and $t = 2\ s$ an exponential temperature decline is observed. Furthermore the heat coefficient goes up and down although it should be constant yielding in a rough average of $\alpha = 8\ kW/m^2K$.



(a)



(b)

Figure 4.3: (a) Heat Transfer Coefficient (b) Surface Temperature over Time

Chapter 5

Conclusion

Several facts limit the precision of the determination of the heat transfer coefficient α. First, the calibration is made in a quasi-static way. But the experiment is transient and in this short time scales the Liquid Crystals might not show the same behavior as in the quasi-static case. Another significant error is the timing of the opening of the valves and the start of the MATLAB code that acquires the data. Additional time offset is implied by long hoses. When we performed the experiment, something went wrong in the timing and the measured data was useless.

The simplified experimental setup makes it impossible to match all Dimensionless Parameters. Although Reynolds Number is in the same order of magnitude, Prandtl and Nusselt Number didn't match at all. In addition, the function that calculates numerically a value of alpha has a very large searching interval which might reduce precision. It is as well questionable if we really have a semi-infinite configuration. The temperature on the back changes in the course of our measurement. A heating or a insulation would probably reduce the drop of the backside temperature.

The TLC used in this experiment don't have a very large temperature range. In our experiment there was also clearly an asynchrony between the water pulse and the camera. Both factors combined led to very poor results.

5.1 Potential Improvements

To become better results there are some factors that could be improved. First of all, the liquid crystal membrane could be replaced by one with a better temperature range. On the other hand a little trigger connected to the computer could be used to synchronize the temperature-change pulse so that the camera takes the shots at the right time, as soon as the valve is open.

5.2 Outlook And General Conclusion

Unfortunately, the results of this experiment were rather disappointing, although we were able to get a good insight of how this kind of measurements for the industry could be performed. Too many practical errors played a role in this experiment, so that all our results were only to be dismissed and even the ones provided by previous "more correct" runs were not as optimal as expected.