Heat Transfer Analysis Using Thermochromic Liquid Crystal

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1 Introduction

The goal of our experiment is to determine the heat transfer coefficient of a heat exchanger using a thermochromic liquid crystal foil. In this specific case the heat exchanger acts as a cooling device of a turbine blade.

Turbines are often used in a high temperature environment, where the temperature exceeds even the melting point of the turbine material. This is the case, because the temperature of the fluid in the turbine is highly affecting the efficiency of the whole process, which basically increases with increasing temperature.

To prevent the melting of our turbine and therefore failure of the whole process we need a reliable cooling system. In most applications the cooling fluid in a turbine is a gas cooling the blade from the inside by convection and insulating the blade by forming a thin film around the whole blade.

This causes an optimization problem between the temperature of the working fluid and the cooling system, taking into account that cooling needs energy too.

Before the start of our measurement ($t < 0$) the cooling system has been filled with water of uniform temperature $T_i = 45.2\ °C$ for a sufficient long time that the aluminum plate, representing the surface of the blade, is at uniform temperature.

On this plate a sheet of thermochromic liquid crystal is applied to measure the surface temperature. The whole system, "turbine" blade and cooling channel, is covered by a plate of plexiglas to allow the observation of the temperature change on the metal surface. A camera placed in front of the plexiglas is directed towards a small area in the center of the second pass and will record the change in color of the liquid crystal, as our "blade" is being cooled down.

The camera is linked to a computer where a ready MATLAB-file will save and process the recorded pictures.

To start the experiment we open a valve, allowing cool water at temperature $T_\infty = 24.1\ °C$ to enter the heat exchanger. The camera records the change in colour of the TLC-foil with time. The end is determined either by the time the back of the aluminum plate is cooling down and semi-infinite slab conditions are violated (see chpt. 2).

2 Theory

2.1 Thermochromic Liquid Crystals

Thermochromic Liquid Crystals have the particular feature of reflecting Light of different wavelengths depending on the temperature. This effect is due to the molecular structure of the liquid crystals. The color is a direct measure for temperature. The liquid crystals are not reflecting much light at high or low temperatures (they appear black). It is only in a small temperature range, that visible Light of varying colors is reflected.

Thermochromic Liquid Crystals are available as thin foil or even as paint. It is a cheap method to measure Temperature on an surface. A disadvantage is that the effect of the changing colors is slightly slower than the change of temperature. This is relevant in the case transient processes are observed.

2.2 Our Experiment in Theory

In this section the purely theoretical aspects of our experiment are described. The experiment setup (section 1), the results (section 3) and the difference between theory and reality (section 4) will be treated separately. The goal of the theoretical analysis, is to obtain an expression that will allow us to calculate the heat transfer coefficient from known temperatures and known material properties.

2.2.1 General Assumptions

As a first simplification we consider heat fluxes in one direction only, as described by q_1 and q_2 in figure 1. As a second simplification we assume that we can treat the aluminum as a semi infinite body. The semi infinite body assumption is reasonable as long as $Fo = \frac{x^2}{at} > 1$ where a stands for the thermal diffusivity. This leads to a limitation of the measurement time that can be estimated around $t_{measure} = 1.6\ s$. Of course heat transfer through radiation is neglected as well.

2.2.2 Solution

For $t < 0$ nothing interesting is happening. We assume that water and aluminum are at the same initial temperature T_i and that this temperature is known. Therefore no heat will be exchanged. Whether the water is flowing or not doesn't really matter in terms of heat flux, since there are no temperature differences at all.

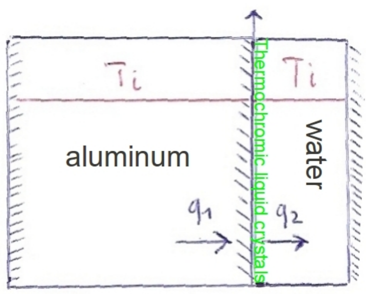

Fig. 1: Situation at $t < 0$.

At $t = 0$ the temperature of the water changes instantaneously to a lower temperature T_∞ that is known as well. We assume that the temperature of the water can be described by the *Heavyside step function*. The TLC sheet located at the water-aluminum interface is assumed to measure the wall temperature.

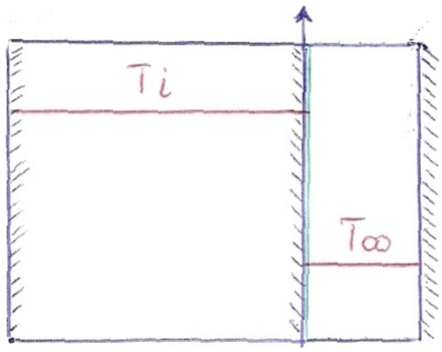

Fig. 2: Situation for $t = 0$.

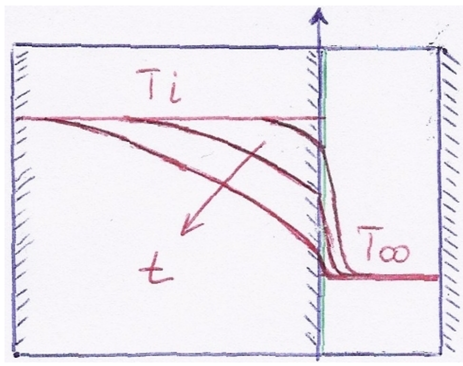

Fig. 3: Situation for $t > 0$.

Starting from $t = 0$ (t_0) heat will be transferred due to temperature differences. As a consequence the aluminum temperature will decrease until it reaches T_∞ and the water adjacent to the wall will become slightly warmer. The assumptions here are, that we still know the water bulk temperature T_∞ and that this temperature and T_i remain constant (semi infinite body).

To relate α with known values we will determine the temperature of the wall as a function of time considering the aluminum part and using the semi infinite body assumption. Three boundary conditions will be necessary one of which will be obtained from a simple energy balance.

Convection occurs in the water (equation 1) and conduction occurs in the aluminum (equation 2).

$$Q_2 = A\alpha(T_\infty - T_{wall}(t)) \tag{1}$$

$$Q_1 = -A\lambda_{Al} \cdot \frac{\partial T}{\partial x} \tag{2}$$

The surface A, the temperature difference $T_\infty - T_{wall}(t)$ and the thermal conductivity λ_{Al} of aluminum are assumed to be known. The heat transfer coefficient α however is what we are trying to determine.

We are now seeking a formula for the temperature at the wall. Since the conduction is transient, we must solve the following differential equation:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} \tag{3}$$

Again we assume that the thermal diffusivity a of aluminum is known. To solve for the temperature as a function of time and space, we need three boundary or initial conditions. The initial condition is obvious: $T(x, t = 0) = T_i$. One boundary condition can be obtained from the semi infinite body assumption: $T(x = \infty, t) = T_i$. Finally by stating that $Q_1 = Q_2\ \forall t$ we find the third condition: $-\lambda_{Al} \cdot \frac{\partial T}{\partial x}|_{x=0} = \alpha(T_\infty - T_{wall}(t))$. Setting now $x = 0$ (at the wall) we obtain the following result:

$$\frac{T_s - T_i}{T_\infty - T_i} = 1 - exp\left(\frac{\alpha^2 at}{\lambda^2}\right) Erfc\left(\frac{\alpha\sqrt{at}}{\lambda}\right) \tag{4}$$

We can't analytically solve for alpha, but we know all the values except α. Therefore MATLAB can solve for alpha by iteration and we have reached our goal.

3 Results

3.1 Calibration

When ever one makes an experiment it is very important to calibrate the instruments one is using. In our case this is the TLC-Foil. Two main reasons demand this calibration: 1^{st} the surrounding conditions (e.g. light influences or temperature influences by air conditioners or windows) might not be the same as at reference location and time. 2^{nd} with this TLC sheet you want to exactly know which color refers to which temperature.

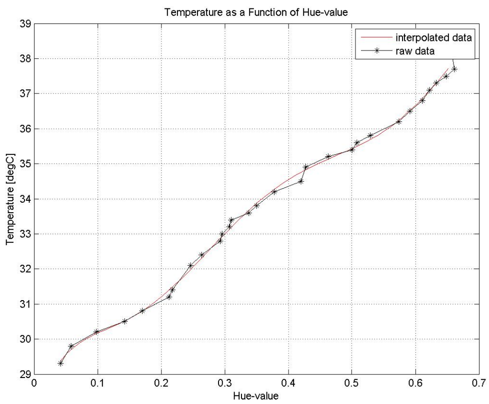

Fig. 4: Calibration curve of the TLC sheet.

Such a calibration can never cover all possible temperatures. Therefor one needs to interpolate after taking a few measuring points. After knowing the RGB-values for a certain color one has to transform those values in to the HSI color space. The result of such a calibration is seen in figure 4.

3.2 Heat Transfer Coefficient Result

For α we would expect a rather constant value and no time dependence. As it's easily cognizable in figure 6 there is simply NO constant section.

For the rearmost part we have an easy and very logical explanation why α is not constant. Let's take a look at figure 5. There we see that the surface temperature stays constant at $T_s = 29.1\ °C$ from the time $t_{const} = 2\ s$ onwards. This is due to the limited temperature range of our TLC sheet which ends obviously at this specific temperature. Of course if T_s stays constant the left hand side of equation 4 stays constant but on the right hand side t still varies and therefor α has to change as well.

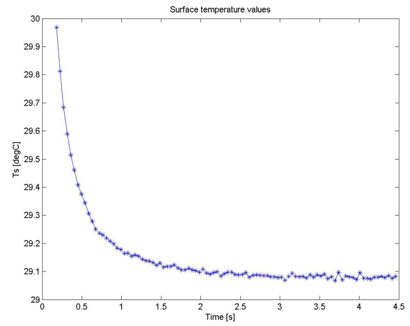

Fig. 5: Plot of the surface temperature T_s against the time t.

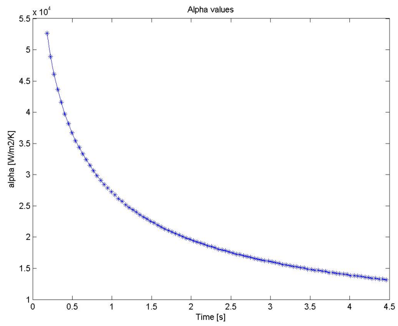

Fig. 6: Plot of the heat transfer coefficient α versus the time t.

Let's now have a closer look at why the first part of the plot in figure 6 is also disturbed. There are a lot of possible reasons for the unsteady developing of the α values. In fact these also influence the rearmost part that we discussed above.

Maybe the most important one is that there was a time lag due to bad timing of opening the valve and starting the recording program. Also there is a relatively long duct leading the cooling water from the valve to the actual experimental device. The cold water pulse (see also section 2.2) therefor needs a certain amount of time to get from the valve to the test section. All these little time offsets lead to a resulting offset Δt. The recording program takes it's start as $t = 0 = t_0$ but in reality the experiment might have started Δt earlier (in our case) or will in fact start this time offset later. From now on the time t and the measured surface temperature T_s don't belong together anymore which causes this now observed developing of α.

Another important malfunction source is that as soon as one opens the valve to let the cold water in, it mixes a bit with the warm water behind the valve. This leads to the fact that we have no longer the assumed step function in magnitude of T_∞ at time zero.

In our specific case also the air conditioner was running during the experiment. This of course cools the hind surface of the baseplate even more down which is in conflict with the assumption that we have a constant T_i far away from $x = 0$. So made a long story short it is no longer an ideal semi infinite body problem.

With this experiment we wanted to find out if those v-shaped rips lead to a better cooling. A good way to do this is to compare the Nusselt Numbers of both cases with each other. This dimensionless number is defined in equation 5.

$$Nu = \frac{\alpha L}{\lambda} \tag{5}$$

As we can see there is a linear correlation between α and Nu. By building the ratio $\frac{Nu}{Nu_0}$, where Nu_0 the Nusselt Number of the smooth case and Nu the one of the channel with the rips is, and plotting it over t we can compare the two cases in an easy way. The result can be seen in figure 7.

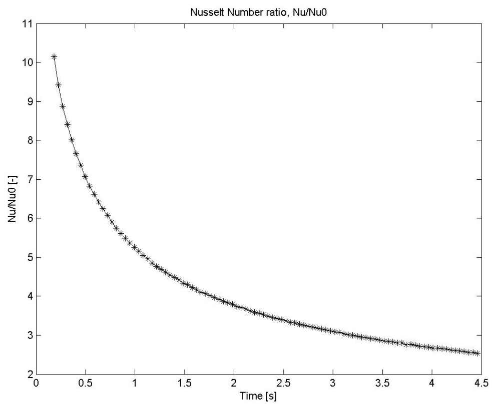

Fig. 7: Comparison of the Nusselt Numbers of the v-shaped rips with the smooth case.

The $\frac{Nu}{Nu_0}$ ratio is always bigger than 1. This means the case with rips is as expected better than the smooth case. The developing of the mentioned ratio is due to linearity in α similar to the one in figure 6. Of course the reasons for this developing are the same as the ones for the developing of α vs. t.

4 Conclusion

4.1 Our Results

The results we got in this experiment are not useful to make general conclusions. One reason is that the Reynolds Number matched but the Prandtl Number didn't. So we can compare different rips or fins but we cannot really compare our case with a real turbine blade.

As we see in figure 6 there is absolutely no constancy of α. So we cannot give a reliable value for α. One should improve the experiment to do so.

4.2 Experiment Improvements

As we saw in section 3.2 it would have been very important for the whole experiment to have the right timing. This problem could be easily solved by adding a thermocouple at the inlet of the test section. With this signal one could trigger the recording of the data and therewith have a t_0 that matches with the incoming of the magnitude step function of T_∞.

To have good results it is always very important to keep the real conditions as close to the ones assumed before hand. For example it might have helped to isolate the baseplate on it's backside to keep T_i constant and therewith the semi infinite body assumption true.

Also one should definitely do more than just one measurement to have a good result. Here we unfortunately didn't have the time to do so.